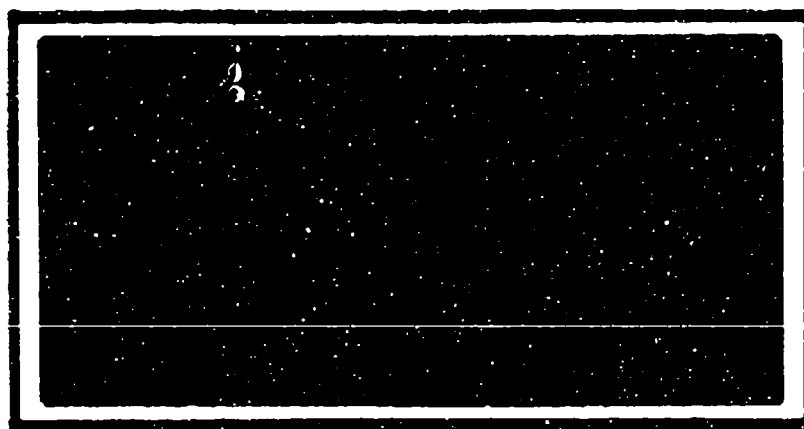


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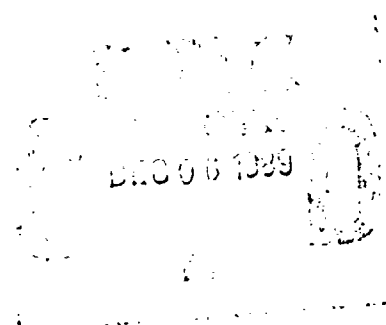
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THE FUTURE OF AIRCRAFT
PAINT REMOVAL METHODS

THESIS

Michael J. Then, Captain, USAF

AFIT/GLM/LSM/89S-67



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THE FUTURE OF AIRCRAFT PAINT REMOVAL METHODS

THESIS

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Logistics Management

Michael J. Then, B.S.

Captain, USAF

September 1989

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Preface

The purpose of study was to develop a qualitative forecast for predicting aircraft paint removal methods. A Delphi methodology was used to create a technical forecast, combining the expectations of individuals who work with the related technologies on a daily basis. The study's main objective predicted the paint removal methods likely to suit future needs. Further investigative areas forecasted: the research and development efforts the new methods will require; the worker safety considerations impact on paint removal methods; the environmental regulations impact on paint removal methods; and the application equipment the new methods will require.

In performing the Delphi and writing this thesis I have had a great deal of help from others. I am indebted to my thesis advisor, Lieutenant Donald C. McNeeley, USN, and Lieutenant Colonel Phillip E. Miller, USAF, for their enthusiasm and patience displayed throughout this exercise. A word of thanks to all of the individuals who devoted the time necessary to accurately complete the Delphi questionnaires. Finally, a very special thanks to my wife Leslie for her love, patience, and encouragement during my AFIT studies.

Michael J. Then

Table of Contents

	Page
Preface	ii
List of Figures	vi
List of Tables	vii
Abstract	viii
I. Introduction	1
Chapter Overview	1
Definition of Terms	1
Background	2
Specific Problem	6
Investigative Questions	6
Scope and Limitations	7
Potential Contributions	8
II. Literature Review	9
Chapter Overview	9
Introduction	9
Chemical Paint Stripping	10
Plastic Media Blasting	16
Laser Paint Stripping	23
Robotics	32
Chapter Summary	36
III. Methodology	37
Chapter Overview	37
General Description	37
The Delphi Process	38
Expert Selection	41
Questionnaire Development	43
Statistical Concepts	46
Analysis Method	48
Chapter Summary	49
IV. Analysis and Findings	50
Chapter Overview	50
Data Collection Process	50
Round One	50
Round Two	52

	Page
Round Three	52
Overall Delphi Results	53
Investigative Question #1 Analysis	54
Findings for Investigative Question #1	61
Investigative Question #2 Analysis	62
Findings for Investigative Question #2	66
Investigative Question #3 Analysis	67
Findings for Investigative Question #3	71
Investigative Question #4 Analysis	72
Findings for Investigative Question #4	75
Investigative Question #5 Analysis	76
Findings for Investigative Question #5	79
Chapter Summary	80
V. Conclusions and Recommendations	81
Chapter Overview	81
Conclusions	81
Conclusion #1	81
Conclusion #2	82
Conclusion #3	83
Conclusion #4	83
Conclusion #5	84
Recommendations	84
Recommendation #1	84
Recommendation #2	85
Recommendation #3	85
Recommendation #4	86
Recommendation #5	86
Further Research Recommendations	86
Research Recommendation #1	86
Research Recommendation #2	86
Research Recommendation #3	87
Chapter Summary	87
Appendix A: Initial Request Letter	88
Appendix B: First Iteration Response	89
Appendix C: Demographic Questions	103
Appendix D: Measurement Questions	108
Appendix E: Second and Third Iteration Comments	116

	Page
Appendix F: Wilcoxon Signed Rank Test Results	143
Bibliography	151
Vita	157

List of Figures

Figure	Page
1. The LASER Process	25
2. The ALPS Project	28
3. The Multiple Laser Process	31
4. Investigative Question #1 Inter-Quartile Ranges	56
5. Investigative Question #1 Inter-Quartile Ranges	57
6. Investigative Question #1 Inter-Quartile Ranges	59
7. Investigative Question #1 Inter-Quartile Ranges	60
8. Investigative Question #2 Inter-Quartile Ranges	64
9. Investigative Question #2 Inter-Quartile Ranges	65
10. Investigative Question #2 Inter-Quartile Ranges	66
11. Investigative Question #3 Inter-Quartile Ranges	69
12. Investigative Question #3 Inter-Quartile Ranges	70
13. Investigative Question #4 Inter-Quartile Ranges	73
14. Investigative Question #4 Inter-Quartile Ranges	74
15. Investigative Question #5 Inter-Quartile Ranges	78
16. Investigative Question #5 Inter-Quartile Ranges	79

List of Tables

Table	Page
1. Personnel Safety Equipment per Aircraft	14
2. Panel Demographics	51
3. Investigative Question #1 Measurement Questions	55
4. Investigative Question #2 Measurement Questions	63
5. Investigative Question #3 Measurement Questions	68
6. Investigative Question #4 Measurement Questions	72
7. Investigative Question #5 Measurement Questions	77

Abstract

The purpose of study was to develop a qualitative forecast for predicting aircraft paint removal methods. A Delphi methodology was used to create a technical forecast, combining the expectations of individuals who work with the related technologies on a daily basis.

The Delphi results yielded five major conclusions. First, the projected paint removal method that will suit future paint removal needs is PMB, and no other method is projected to be a serious threat to PMB's dominance. Second, PMB's process and parameters must be further researched to optimize the method's effectiveness. Third, the worker's safety can be further enhanced by both protective equipment that is available today, and facility construction that is specifically designed for the given removal method. Fourth, facility design is the major consideration when defining a paint removal's environmental effects. Lastly, it is undeterminable if robotics will replace human labor. Equipment that safely applies PMB is available today, while the equipment that further the method's effectiveness of separating heavy particles will be accessible in 1 year.

THE FUTURE OF AIRCRAFT PAINT REMOVAL METHODS

Chapter I. Introduction

Chapter Overview

This chapter introduces the problems associated with current aircraft paint removal practices. Definitions for key terms used throughout the research will be presented, followed by background information that specifies the paint removal dilemma, the research problem statement and investigative questions. Finally, the research's scope and limitations as well as potential contributions to the U.S. Air Force will be introduced.

Definition of Terms

Several terms will be used throughout this study. To aid in understanding these terms, the following definitions are provided.

Airframe: the aircraft's skeleton consisting of the fuselage, wings, stabilizers, flight control surfaces, and landing gear (23:1).

Chemical Stripping: the use of chemicals to remove paint from an aircraft's surface. The chemicals are brushed or sprayed on the paint surface, left to stagnate until

The paint is lifted, and then washed away with high pressured water (38:1).

Composite Structure: a structural sandwich in a layered construction form made by bonding two thin facings to a thick core. The thin facings provide the bending rigidity, while the core grants shear rigidity (15:C12.1).

Corrosion: the deterioration of metal by chemical or electrochemical attack which can take place on the metals' surface or internally. Water or water vapor containing salt combines with oxygen on the metal to form rust, aluminum oxide, metal chlorides, and metal salts (23:171).

Background

The United States Air Force's single largest investment is the purchase of a new aircraft. In the past, the Air Force has procured aircraft readily, with little attention to initiate programs that maximize each aircraft's life span (33:5). Today, with planned defense budget cuts, escalating aircraft costs, and the additional constraints posed by the Gramm-Rudman-Hollings Act, aircraft procurement is limited. In order to provide America with a strong defense posture, the Air Force must have economical programs to increase an aircraft's longevity (46:7-8).

Currently, the Air Force has programs that improve the reliability of existing aircraft through the aircraft's

individual components. These programs emphasize developing higher quality, longer lasting aircraft components. As a result, the Air Force experiences a greater time between component failures and a lowered logistical support cost for each component. The Air Force has found increasing the aircraft's individual component longevity to be an effective way to decrease costs while increasing mission capability (32:5-6). Although these established programs increase individual component duration, the programs fail to emphasize airframe longevity issues.

An airframe's longevity is primarily controlled by its structural durability. The principal element that decreases an airframe's durability is corrosion, which weakens primary and secondary structural members, increases aircraft repair costs, and reduces the airframe's total life cycle (10:138-139). The corrosion process is accelerated by any of the following environmental conditions: atmospheric impurities such as dust or pollution, high humidity, and/or direct contact with salt water. When left unchecked, these conditions accelerate surface corrosion by accumulating on the airframe's surface and corrosively attacking the exterior layer (24:1-4). Maintenance facilities battle surface corrosion primarily through two means: periodic washing and protective painting. Routine washing reduces surface corrosion by removing grease and other impurities from the aircraft's surface that accelerate the corrosion process. The main preventative measure, paint, seals the

airframe's surface from direct contact with harmful atmospheric effects (10:138-139; 24:1-4).

While aircraft are ultimately painted to protect the airframe from corrosion, the paint also serves multi-functional purposes such as providing camouflage, thermal protection, and erosion resistance. During the aircraft's life, paint is applied and removed for a variety of reasons, from replacement of worn coatings to changes in color schemes. As part of the painting process, paint removal is an important initial step assuring a quality re-paint program (20:1).

Because modern aircraft paint is extremely durable and has evolved at a much faster rate than paint removal processes, paint removal is a complex and laborious procedure. The most widely accepted paint removal process, chemical stripping, is a relatively primitive technology that relies on toxic chemicals and physical human labor to remove paint (20:1). Because aircraft are routinely painted every four to seven years, aircraft accumulate a number of touch up coats between painting cycles. To remove the weathered coats of paint, aircraft depots commonly employ chemical stripping in conjunction with high amounts of intensive human labor (9:1). The laborers scrub the paint surface with a wire brush or sandpaper in-between chemical applications to remove the accumulation of paint layers. As a result, the physical work is hazardous to the laborers due to the presence of paint dust or residual chemicals, and can

cause damage to the aircraft's surface when the abrasive cuts through the paint layers and grazes the surface (48:3).

Furthermore, chemical stripping was developed when aircraft were constructed of metal or aluminum and does not cause substrate damage when used on aluminum or metal surfaces. However, modern aircraft are increasingly made of composite structures consisting of epoxy and graphite. Chemical stripping can not be used on the modern surfaces because the chemicals damage the epoxy or graphite composition (48:3; 9:1).

Besides posing severe health issues, chemical stripping also causes environmental hazards. The waste generated from chemical stripping is subject to a host of federal, state, local, and base regulations that impose handling, storage, transportation, and disposal requirements. The price tag associated with the toxic clean-up is staggering and the environmental impact unmeasurable. Up to 1988, an estimated \$312 million dollars had been spent on disposing hazardous waste (including chemical stripping waste) within the Department of Defense, and a projected \$3 billion dollars to clean up existing storage and disposal sites (62:22).

These environmental concerns have forced many government agencies to restrict or eliminate hazardous waste, including chemical stripping (12:1-3). As an example, the state authorities in North Carolina and the Environmental Protection Agency were concerned about the pollutants being released into the Neuse River, and imposed

strict water pollution controls in 1984. As a result, the Naval Aviation Depot located at Cherry Point, NC, almost stopped their paint stripping actions because of the chemical stripping waste they released into the river (29:12). Hazardous waste's environmental impact has forced Congress to pass a law ordering all private and public agencies to reduce hazardous waste usage by 10% per annum until 1992. Consequently, the Air Force initiated the Pacer Reduce Program that will reduce disposable hazardous waste produced by Air Force installations by 50% between 1984 and 1992 (62:22-25).

Chemical stripping is an outdated paint removal method threatened by mandatory reductions in hazardous waste, laborer health issues, expensive waste disposal, and effects on composite surfaces. Because of these elements, it is clear a new paint stripping technology is needed (62:22-25).

Specific Problem

Current aircraft paint removal methods are outdated for today's paint removal requirements. Present paint stripping technology can cause health, environmental, and technical problems, thus being inadequate for future paint stripping demands. What steps will the aerospace industry proceed through in the next 15 years or more to obtain a solution to the current aircraft paint removal situation?

Investigative Questions

A series of questions were examined to determine what

will be the forecasted paint removal method, and the iterative steps that will be required to arrive at that method. The questions are:

1. What paint removal methods are likely to suit future needs?
2. What research and development efforts will the new methods require?
3. What worker safety considerations will impact future paint removal methods?
4. What will be future paint stripping environmental regulations?
5. How will future paint stripping methods be applied?

Scope and Limitations

There are many technical, economical, and environmental elements that would impact any projected paint removal method. The scope of this investigation was limited to the main issues influencing each element, especially within the technical fields. This research will present a literature review investigating current paint removal technology, offering knowledge of present paint stripping research and practices. A Delphi forecast will use a consensus among paint removal experts to predict the iterative steps in obtaining the forecasted method.

The investigation is limited by the selected experts' knowledge and experience level. There are many different specialties within the paint removal field, with more specialties added as new technologies developed. Omittance of a particular specialty though the expert selection process could bias the Delphi forecast.

Potential Contributions

This study can be used by logisticians in evaluating current and potential paint removal technologies at an aggregate level for developing long-range resource plans. Through use of the Delphi process, depot paint removal facility and equipment needs can be forecasted. The forecast will avoid expensive equipment purchase or facility construction that prematurely become obsolete. Additionally, scarce funds appropriated for paint stripping research can be funneled into the most promising areas, accomplishing more detailed research for the same amount of money.

The Delphi process can also be used by engineers as an information exchange, showing both the group's consensus on the future of paint removal methods, and individuals' thoughts on specific aspects.

Chapter II. Literature Review

Chapter Overview

This chapter presents the predominant paint removal method, chemical paint stripping, plus two other removal methods: plastic media blasting and laser paint stripping. This study will concentrate on present technology in each of the three methods, plus provide a supplemental section on robotics. After a brief introduction, each of the method's technical procedures, histories, and controversial problems will be viewed. Finally, robotic usage in the paint removal field will be presented.

Introduction

The high dollar value associated with modern aircraft coupled with national budget restrictions forces a greater emphasis on extending an aircraft's life cycle (48:8). In the past, the Air Force would replace an aging aircraft and not consider alternatives. Today, the Air Force can not rely on replacement, but must resourcefully derive more life from existing aircraft (32:5-6). One area the Air Force can increase the aircraft's life is through corrosion control (10:138-139). Corrosion is primarily controlled by periodic washing, structural inspection, and painting. Washing removes harmful grease and dirt accumulations that build up on the surface causing corrosion. Aircraft are routinely scheduled for non-destructive structural inspections that

identify corrosive areas. Finally, routine painting of the complete airframe insures sealing the airframe from corrosive atmospheric effects (24:1-4).

Routine painting, however, does require removing the old, weathered paint coatings from the aircraft's surface. The most widely used paint removal technique, chemical stripping, contains toxic chemicals that endanger the technicians health, pose environmental damage, and requires costly treatment and disposal techniques (20:1). Furthermore, chemical stripping is not compatible with materials used on modern aircraft (50:3). Implementation of a new method appears essential. But first what exactly is chemical stripping, and why is it unsuitable for future paint stripping demands?

Chemical Paint Stripping

Other than hand sanding, chemical paint stripping is the oldest and most common paint removal technique. It was developed for removing paint on a metal or aluminum surface, and its actual process is straight forward (25:2). The structural surface is first washed to remove oil, grease, and other surface contamination. Components not requiring paint stripping are then removed or covered with aluminum tape before the technician applies the chemical stripper. The stripper is either sprayed or brushed on the paint surface, and then left for approximately 30 minutes to soften and lift the paint from the substrate. The softened

paint and excess solvent is then removed using hard rubber scrapers, with residual solvent and paint removed by a water rinse. The process is repeated until the chemical stripper is no longer removing paint. At that point manual scraping with wire brushes or sandpaper removes the remaining paint, finishing the removal process (1:7).

There are a variety of chemical strippers, with the proper type of chemical stripper dictated by the type of paint on the airframe. Generally, the more modern the paint on the airframe, the harsher the chemical stripper required (9:1-2; 38:1-2). In the past, aircraft in the Air Force inventory used an acrylic lacquer topcoat paint with a zinc chromate primer. The chemical stripper used for paint removal on older aircraft contained primarily a toxic chemical called methylene chloride. It's preferred over other paint strippers because of its effectiveness on a variety of paints and is biologically degradable (38:2,23). Currently, however, the Air Force paints aircraft with a long lasting polyurethane topcoat and a durable epoxy primer. This new combination of polyurethane and epoxy enhances the paint's wear resistance, but the old methylene chloride based chemical stripper is ineffective in removing the durable paint coatings. Consequently, harsher chemicals, such as phenols and amines, were added to the methylene chloride based stripper to aggressively remove the modern paint coats (38:1; 20:1). Phenols and amines were found more effective than methylene chloride in removing the

newer epoxy primers and polyurethane topcoats, but their use presents ecological problems. For example, the use of phenols was found to cause severe water pollution problems because the chemical is not biodegradable (20:1).

The use of phenols and methylene chloride in paint strippers along with other hazardous waste producing process has caused agencies at the national, state, local, and base levels to implement a host of laws and regulations concerning waste generation, handling, storage, transportation, and disposal (12:1-4). At the national level, the Environmental Protection Agency (EPA) has introduced numerous acts that regulate industrial hazardous waste. The three predominant acts created by the EPA that effect chemical stripping addressing minimum worker safety and environmental impact issues are the Occupational Safety and Health Act, the Clean Water Act, and the Clean Air Act. As a result, the aerospace industry has been forced to restrict chemical stripping because of worker health and environmental issues (62:21; 12:1-4).

To exemplify the effects at the state level, the Naval Aviation Depot at Cherry Point, North Carolina, almost closed when forced to adopt a different paint removal operation because of state regulations. The depot facility was stripping F-4 type aircraft with phenolic based chemical strippers, with each aircraft requiring three to four 55 gallon drums of solvent. After the paint stripping process, the waste was partially treated to remove some of the

phenolic chemicals and transported to the associate Marine Corps Air Station for further treatment. At the Marine Corps Air Station the phenolic concentration was reduced to an average of 55 parts per million (ppm), and then released into the neighboring Neuse river. These discharges were sanctioned under the EPA's clean water act; however, in 1984 the state viewed the concentrations harmful to shellfish and imposed regulations requiring the phenolic count discharge limit of 1 ppm. Existing technology could have reduced the phenolic count to 2 ppm, but such a treatment would have cost \$1500 per 55 gallon drum of stripper and still would fail to meet the discharge restrictions. As a cost effective alternative, the depot adopted a less aggressive, non-phenolic paint stripper until a better solution is found (29:12,92).

The chemical stripper's toxic waste not only causes regulatory problems, but also jeopardizes the health of workers administering and handling the chemicals. Besides burning exposed skin when contacted, these chemical solvents also release volatile organic compounds (VOC) that produce carcinogenic side effects. The VOCs primarily affect personnel in the immediate stripping area, but could impact anyone living by the stripping facility if proper handling and disposal procedures are not followed (18:2). To protect the worker from possible burns and carcinogenic fumes, disposable safety equipment must be worn. The average type, amount, and cost of personnel safety equipment required to

chemically strip an F-4 type fighter aircraft is shown in Table 1. The carcinogenic fumes produced also influence stripping facility design. Because of OSHA and the clean air act, minimum work area ventilation and air filtration methods ensuring safe worker conditions and environmentally clean air must be met (41:15).

Aside from being subject to restrictive laws and causing health problems, chemical stripping is incompatible with modern composite aircraft surfaces (60:6). A study performed at the Naval Air Development Center in Warminster, Pennsylvania investigated the effects of graphite/epoxy composites when treated with commonly used epoxy/polyurethane type paint strippers. The study found that these strippers caused a loss in the composite's physical properties, especially with the strength of the surface material. Consequently, the study recommended that these common paint strippers should not be used on epoxy/graphite surfaces (60:6).

Table 1: Personnel Safety Equipment per Aircraft (41:15)

ITEM/DESCRIPTION	QUANTITY	COST(\$)
Paper Suits	6 cases	240
Rubber Gloves	120 pairs	57
Replacement Shields	32	53
Goggles	6	10
Respirator Cartridges	60 sets	112
Filters for Cartridges	60 sets	32
Total Cost per Aircraft		504

Finally, while chemical paint removers are considered safe on aluminum and metal surfaces, many air carriers periodically inspect their airframes' surface for hydrogen embrittlement as precautionary measures. Chemical solvents can damage and corrode an aluminum or metal surface when the solvent is not completely rinsed off before painting. Hard to rinse areas, such as corners and underneath rivet heads, are subject to corrosion when chemical stripping is used. Thus, even the advantage that chemical stripping has of being safe on aluminum and metal surfaces is jeopardized when caution is not exercised by the technicians (18:2).

In search for an alternative method, the Air Force Logistics Command in 1980 initiated several investigations into nonchemical paint removal methods. These studies took place primarily at Hill AFB, Utah, and were technically assisted by the Wright Aeronautical Laboratories at Wright-Patterson AFB, Ohio. Hill AFB, the depot for the F-4 type aircraft, was a logical location to perform the studies because of the base's extreme chemical stripping reliance. Numerous paint removal techniques were invented, adopted, or modified from related technologies to replace chemical stripping. Among the investigated methods, only two techniques appeared promising: plastic media blasting and laser stripping (53:64).

Plastic Media Blasting

One of the promising paint removal techniques developed in the late 70s and adopted for aircraft use is plastic media blasting (PMB). PMB technology was evaluated for aerospace use in the early 80s at Hill AFB, Utah, the F-4 fighter aircraft depot (17:411-412). Due to the F-4's age, many different coats of epoxy, polyurethane, and enamel paint have been applied to the aircraft's surface in between complete depaint/repaint practices performed at the depot. Consequently, harsh chemical strippers were required to removed the weathered paint coatings, which generated 210,000 gallons of contaminated waste water daily. Because of the base's dependency on chemical stripping, an extended development effort was created for PMB in 1983 called the Productivity, Reliability, Availability, and Maintainability (PRAM) project. The PRAM project acquired PMB blast equipment, developed operational parameters, and trained personnel for equipment use (16:1-2). The PRAM project was supported through the Wright Aeronautical Laboratories at Wright-Patterson AFB, Ohio, who technically analyzed the project. By July 1984, the first F-4 aircraft was ready for production PMB paint removal (53:64; 16:1-2).

While the Air Force was investigating PMB, other agencies, both DOD and commercial, were involved with PMB research and production techniques. In fact, the first full scale production PMB stripping facility began operation with Republic Airlines, now Northwest, on June 27, 1984 (6:50).

The Army Depot located at Corpus Christi, Texas, began PMB paint removal for composite helicopter components in June, 1984. The Navy started PMB stripping F-4 aircraft in 1984 and has been a leader in the PMB industry ever since. Concurrently, the aerospace industry's PMB acceptance was growing. As of January, 1988, a reported 300 PMB installations were operating worldwide, including installations at large commercial airlines like Delta, Air Canada, and United Airlines (17:411; 54:A-14,A-21).

The PMB process uses small, granular plastic particles (amino thermoset or unsaturated polyester resins) that have irregular sharpened edges. The particles, also called beads, are propelled by compressed air against a painted surface (56:1). The bead's sharpened edges serve as an abrasive to shatter and dislodge paint coatings. Because the plastic beads are softer than the aircraft's surface, PMB supposedly allows paint removal without damaging the substrate (53:64).

The PMB process takes place in a blast room, a facility large enough to house the aircraft and required PMB equipment. Each blast room must be equipped with the following: a source of dry, compressed air; blast machines; media reclamation system(s); and dust handling equipment that properly ventilates the blast room. Dry air is supplied by a properly maintained air compressor. Blast machines consist of two types: direct pressure or suction design. The direct pressure blast machine stores plastic

media in a pressurized container that directs the media through a hose and finally to the blast nozzle. The suction design allows compressed air to expand at the blast nozzle, creating a suction effect. The suction effect pulls the plastic media from a storage container through a hose to the blast nozzle (56:7-21).

As the beads impact the surface, the beads break down in size and create a plastic dust. A percentage of the larger beads are reclaimed for further use, while the smaller beads are discarded with the removed paint chips. The larger beads are recovered, sized, and separated by the reclamation system. During the separation process, the system distinguishes foreign particles, such as paint chips and dirt, from the useable beads and discards the foreign particles with the smaller, unusable beads. The system then cleans the larger beads and reinserts them back into the blast machine. Manufacturers estimate 90% to 95% of the beads can be reclaimed after each use, and the beads can be recycled between 10 and 20 times before they are too small for reclamation. The dust collection system, a vital reclamation subsystem, removes plastic dust from the blasting environment. The system extracts dust from the reclamation system where used beads are separated by size. The dust collection system also removes dust in the blasting room by circulating ventilated air through a filtering system (56:22-30).

The operator is protected during the PMB process with a full coverage hooded helmet with wide span viewing lens, an air breathing supply with a carbon monoxide monitor/alarm, and a leather faced/cotton backed blast suit with leather gloves (56:8). The equipment protects the worker from all possible health threats except one, explosive dust. The plastic dust created during the PMB process is extremely explosive, with the finer the dust, the greater the chance of an explosion. A study conducted by the Bureau of Mines found that the size and type of plastic media determine the PMB's explosiveness degree. The study concluded that generalizations about the safety of blast systems, plastic media type and size, or blasting parameters could not be individually determined without considering the dust collection system as an entity. The study further determined that all of the previously mentioned elements should be correlated when an equipment manufacturer is designing a dust collecting system to limit the plastic's explosive characteristics (27:18-20).

For the worker's health and safety, the dust collection system ventilates the room to maintain low dust levels and clear visibility. Research shows that toxic effects on the worker from PMB dust is minimal; however, harmful heavy metals particles extracted by the process from some substrates are known to cause health problems. To avoid any health related crisis, the concentration of these metals should be monitored for amounts exceeding the limits

established by the American Conference of Governmental Industrial Hygienists (55:42-45).

Besides the minimum operation equipment and worker protection gear, successful plastic media blasting is subject to the proper mixture of inter-related blasting parameters. Parameters are described as hardness of plastic beads (measured in Mohs), plastic bead size (measured in mesh or sieve), and blast pressure (or nozzle pressure, measured in pounds per square inch). Other parameters include the nozzle diameter, distance between the nozzle and the substrate (stand-off distance), and the angle of blast. All of these parameters must be coordinated according to the type of substrate underlying the paint layers (31:1-7; 27:3). Determining the exact parameter levels requires operator experience and proper training, otherwise substrate damage can result. Because experience prescribes success, a sustained worker training program must be a part of a PMB implementation and continuous program operation (54:A-17, A-18).

Even though blasting parameters can be calculated for a given aircraft surface, tests have reported mixed conclusions about PMB's harmful substrate effects. The PRAM project reported PMB is not always a complete stripping method; some substrates will have to be chemically stripped because of PMB's damaging effects. The report further states that PMB should be used with extreme caution on very light or thin metals and very soft metals (16:4-6). A study

sponsored by the Naval Facilities Engineering Command of various DOD PMB facilities stated "...any operation in which an abrasive is impacted onto a substrate produces some sort of effect on that substrate" (56:46). To avoid detrimental surface effects, careful media selection and parameter controls were recommended. Though the study revealed negligible damage to substrates in most cases, three facilities reported crack formation when using PMB on various aluminum alloys. The report concluded if crack detection is suspected, non-destructive ultrasonic testing should be employed (56:46-47). Another study performed by Battelle located at Columbus, Ohio, studied the parameters that effect crack rates. The study concluded that media selection has the single largest correlation with crack formation, although the result is not conclusive (30:237).

Despite warnings of substrate damage, many installations use PMB with successful results. As a demonstration to skeptics, a PMB equipment manufacturer removed paint from a thin aluminum soft drink can without denting or penetrating the soft metal (53:66). The Corpus Christi Army Depot uses PMB for paint removal on composite and thin aluminum surfaces without causing substrate damage. The Coast Guard's Aircraft Repair and Supply Center has experienced various degrees of success with PMB stripping on composite surfaces. The Coast Guard describes the process as "an operator's art," and accounts PMB stripping variations to the operator's experience in removing too many

paint layers and penetrating the substrate (34:82). Studies conducted by Battelle Memorial Institute concluded substrate damage is caused by foreign particle contamination introduced during the reclamation cycle. The heavy particles are propelled with the plastic beads and cause cracks when impacted against the substrate. Thus, the equipment that controls the parameters and reclaims the media has a serious effect on the PMB process (8:207).

Although PMB is an environmental improvement over chemical stripping, PMB does generate solid hazardous waste. The hazardous waste is created by the concentration of metal particles extracted during the PMB process from the substrate and collected with the plastic dust. The small amount of metal particles contaminates the dust collected during the process, resulting in more hazardous waste than chemical stripping for a given area (55:31). A number of methods are under study by the Air Force to reduce the hazardous waste's weight. Screening to separate the hazardous and nonhazardous waste reduces the hazardous waste volume by 20%, but the percentage is not high enough to justify the implementation costs at PMB stripping facilities. Incineration of PMB can result in a reduction of weight by 95% or greater, however this method is still under investigation (55:46-47).

While plastic media blasting is an improvement over chemical stripping dilemmas, it is by no means perfect. The process still endangers the worker's health, can damage any

substrate, and produces solid hazardous waste. A possible solution to PMB's contrary results is a technique under extensive investigation: laser stripping.

Laser Paint Stripping

A laser is a device which amplifies focused light waves and concentrates them into a narrow, intense beam of energy (45:103). Through this fundamental technology, laser based systems are used in many processing applications in industries such as medicine, metal working, and electronics. Laser surgery is increasing popular in the medicine field, with the laser beam defining a precise incision that speeds the patient's recovery. The metal industry has increased production times with lasers for welding, soldering, and cutting. Lasers are economically used throughout the electronic field by boring precision holes in circuit boards. Because the laser's narrow beam of energy offers multiple uses, lasers are adaptable to an increasing number of processing situations. During the early eighties, lasers were investigated as an alternative to chemical stripping for aircraft paint removal (3:1; 50:1-6).

The word LASER is an acronym which comes from the phrase Light Amplification by Stimulated Emission of Radiation. The light produced by a laser is quite different from ordinary light (19:4). Naturally generated light is not coherent because the source is based on a naturally uncontrolled random process of atoms and molecules emitting

light such as heating and burning. The light from a laser is coherent because the source is artificially controlled (36:140). The light is controlled by three major elements: the medium, an energy source pump, and an optical cavity. The medium contains element(s) that emit photons when a catalyst source of energy is introduced. The pump introduces the catalyst energy under a controlled process that excites the medium (19:5-7). The optical cavity contains two reflectors that mirror the emitted photons, further exciting other atoms to emit photons. After a gradual build up of photons is produced by the optical cavity, the laser beam is then discharged through a specific portion on one of the reflectors (36:140-142). This process is represented in the system diagram in Figure 1.

The major distinctions that identify different laser types is the element used for the medium and the method of reflection control. A common form of medium element include a gas medium which is primarily composed of helium and neon (36:139-140). Another type of common medium is the solid medium, using either ruby crystals or yttrium aluminum garnet (YAG) elements (59:5). Reflection control is performed by either a continuous wave or a pulse technique. The continuous wave reflects the excited photons so that the number of photons created equals the number generated in the output. The pulse technique uses a rotating prism as one of the reflectors, and controls the photons so output is created in surges instead of continuously (19:9).

Laser paint removal was not a concept generated in the early eighties, but was initially developed in the sixties. Early experiments failed due to four common technical problems. First, the early laser beams used a continuous output of energy (called a continuous wave) that forced the beam to be in constant motion to avoid concentrating too much energy and burning the substrate. Secondly, the beams lacked homogeneity, which produced energy eruptions and charred the substrate surface. The third problem encountered was the laser could only remove paint from flat surfaces and could not conform to the aircraft's surface

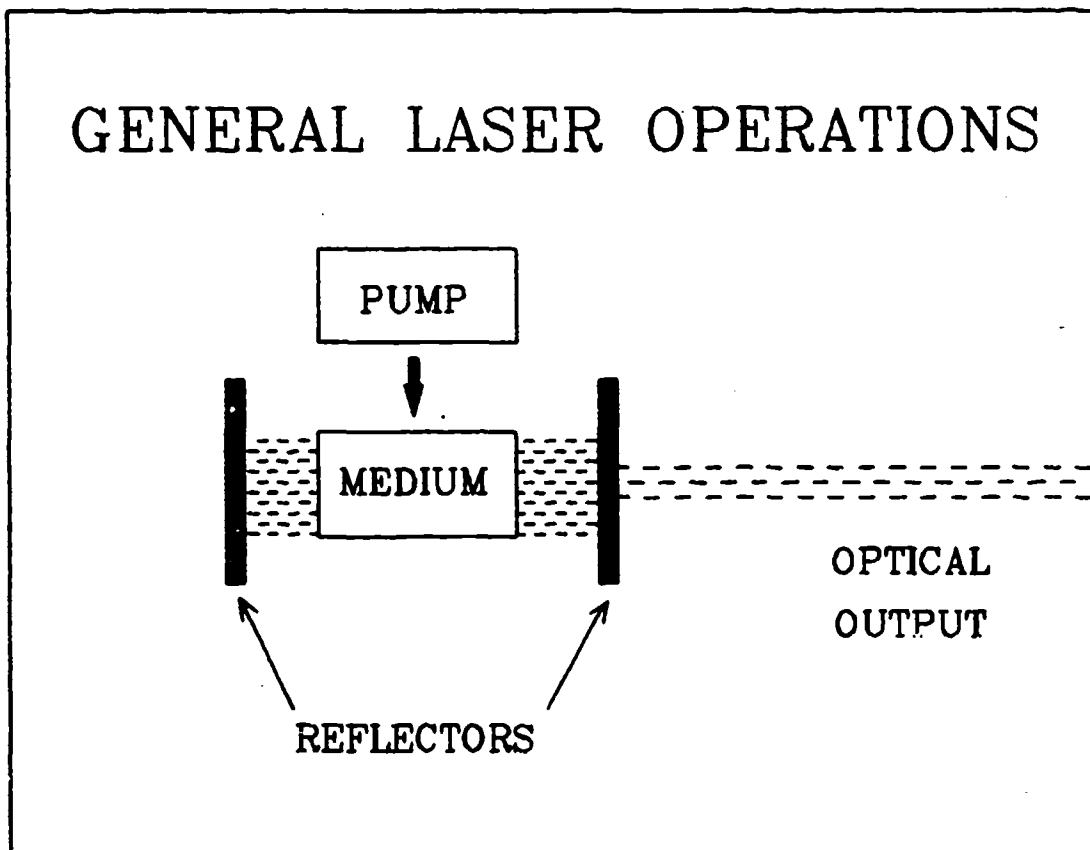


Figure 1: The LASER Process (36:141)

curvatures. Lastly, the early lasers were fragile, and easily damaged because of dirt, vibration, and noise in the paint removal environment. After the initial research in the sixties, scientists concluded the previously mentioned items needed resolving before paint removal could be accomplished with laser technology (50:1-8).

During the early eighties, an investigation exploring aircraft paint removal with lasers was requested by the Air Force, and conducted by Avco Everett Laboratory and the Grumman Corporation. Due to laser technology advancements since the sixties, the study concluded that lasers offered promising paint stripping capabilities, but Avco was unable to simulate an aircraft paint removal environment because their laser was not portable. Consequently, Grumman teamed with two laser companies, INTA and Coherent, who offered portable lasers. The laser was coupled with a programmable robotic aircraft painting system developed by the CGA Corporation and Gilbert-Commonwealth Corporation. Although the study united the smaller laser with a robotic system, conclusions were made that the laser beam's control through the robot was unmanageable and produced a safety hazard to anyone in the immediate area (41:20-21).

The Air Force continued its laser feasibility investigation with the Small Business Innovation Research (SBIR) program conducted through Laser Technologies. Phase 1 of the study used a high powered, pulsating laser that produced homogeneous beam characteristics. Knowing that

laser paint removal had been proven feasible through previous investigations, the study investigated the types of by-products produced during laser operation and substrate analysis. Conclusions of Phase 1 indicated that harmful aromatics were produced with laser paint stripping; with the amount produced dependent on the beam's energy level, the type of paint being stripped, and the amount of paint removed. The study further revealed that laser stripping should not attempt to remove all of the primer coat when used on carbon fiber composites. When the process attempts to remove all of the primer, substrate removal is inevitable due to the substrate's microscopic roughness. Finally, the research showed some surface deformities due to the beam's intense heat. The deformities were inconclusive, but critical enough to schedule further surface analysis in the next research step, Phase 2. (49:1,18-21).

With preliminary laser stripping studies indicating a promising removal method, the Navy contracted research with Martin Marietta's Enrichment Technology Application Center. Since research with laser stripping was not compared to other methods, the research's exploratory phase investigated laser stripping to plastic media blasting. The results showed that laser stripping is less aggressive, leaving a cleaner surface than PMB. Furthermore, the study achieved a 2 to 5 square feet per minute removal rate and concluded the rate could be scaled up for economical paint removal (2:171-178). The exploratory research justified further research

that will consist of two phases. Phase 1 will optimize the laser parameters, develop an economical paint removal rate, and determine the effect on curved surfaces. Phase 2 will use the information gathered in Phase 1 and develop an easily operated hand held laser system that uses an optical sensing device to establish the proper laser beam. Phase 2 will also develop redundant safety systems to prevent operator eye injuries (3:1-58).

Another laser based paint removal system the Navy is developing jointly with the Air Force is called the Automated Laser Paint Stripping of Aircraft (ALPS). This

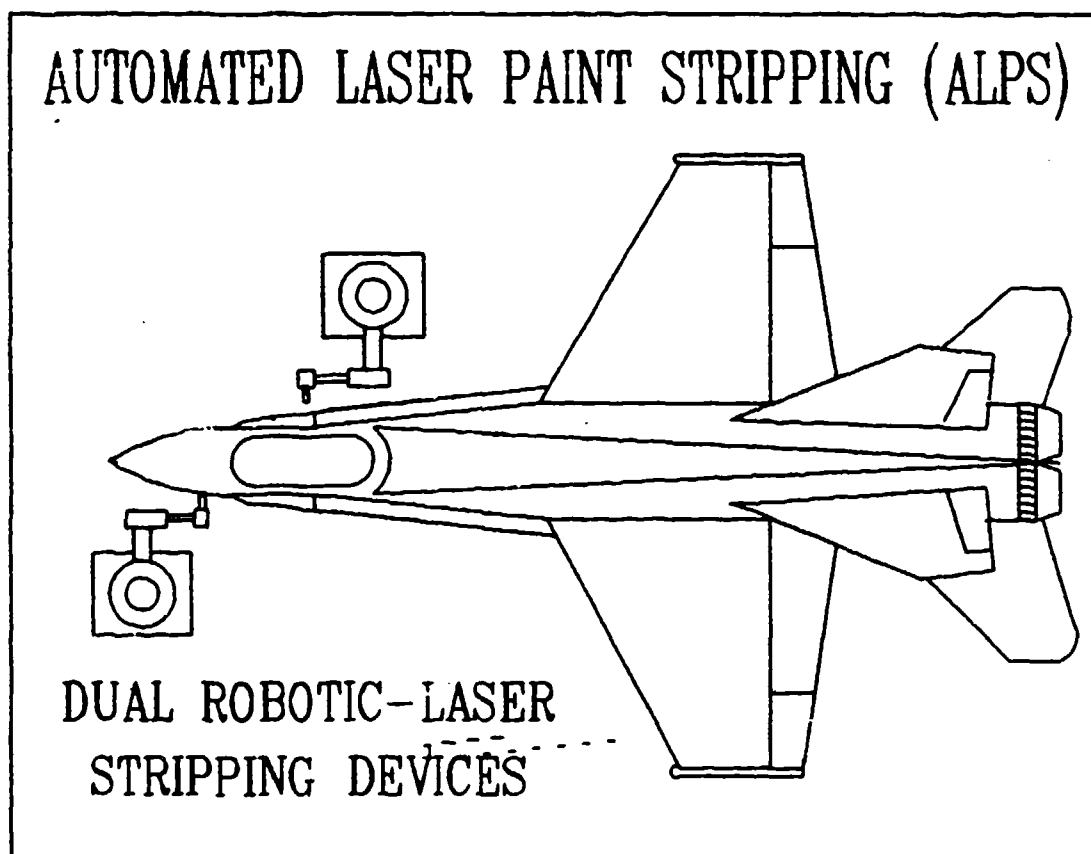


Figure 2: The ALPS Project (7:2)

proposal integrates a pulse lasers, vision system, sensors, and robotics to strip paint from fighter aircraft and helicopters. Although the program is in its initial development, the system will consist of dual wheel mounted robots that will provide redundancy and increase throughput. As depicted in Figure 2, the robots will be capable of independent operation using pulse lasers. The lasers are robotically controlled though a microprocessor that is linked to visual sensors and feedback controls, allowing precise cutting depth (7:1,3).

The Department of Defense is not the only agency interested in laser paint stripping, private companies have been independently exploring the technology. INTA, the company contracted by Grumman during preliminary investigations, has developed an innovative feedback control system. The feedback system allows the laser to sense multiple paint layers, multiple paint colors, surface curvature, and end the operation at a selected layer of paint. All this is possible through a light reflected on the paint surface. The reflected light emits a specific color spectrum which is used by the feedback system in analyzing the type of paint, primer or substrate, the amount of paint layers, and the chemical composition of each layer (45:103-106,120).

Another private company, the Oak Ridge National Laboratory operated by Martin Marietta, has performed an innovative study using excimer lasers with a gas mixture to

remove paint from composite materials. Although the study had a lower removal rate than expected due to manual laser control, the study did reveal some interesting observations. First, the use of lasers to strip paint from composites appears to have no stress effect on the substrate due to heat. Second, a source of feedback control may be possible through color changes in the plasma plume created by the lasing when stripping from color coat to primer. Third, the process control is paramount for successful laser stripping. Fourth, and most important, it may be possible to increase the stripping rate at a proportional rate with multiple lasers. The system, depicted in Figure 3, uses a lens to harness the lasers output into a unified effort (4:1-4). Laser stripping offers some strong advantages when compared to other methods:

1. laser stripping can be used on metal or composite substrates.
2. no taping or masking is required.
3. post stripping operation consists of a standard washing.
4. an economical 3 square feet per minute removal rate is achievable (45:103-106,120).

Furthermore, this method does not produce enormous amounts of hazardous waste, and can remove the worker from the environment when coupled with a robotic system. Although these are strong advantages, laser stripping has to be fully developed before the process can be considered feasible (45:103-106,120).

Some of the disadvantages created with laser stripping is due to the brightness and intensity of the beam. The

principal concern is with eye damage, since the light produced is thousands times more intense than the focusing power of the human eye. Another consideration that escalates with the beams intensity is skin damage. Furthermore, other problems include ionizing radiation, optical radiation, and noise produced during the process. Because of these disadvantages, manufacturers recommend maximum permissible exposure levels associated with each type of laser (19:1-2).

Laser stripping technology is still in the infancy stages. Many technical questions are still unanswered, but

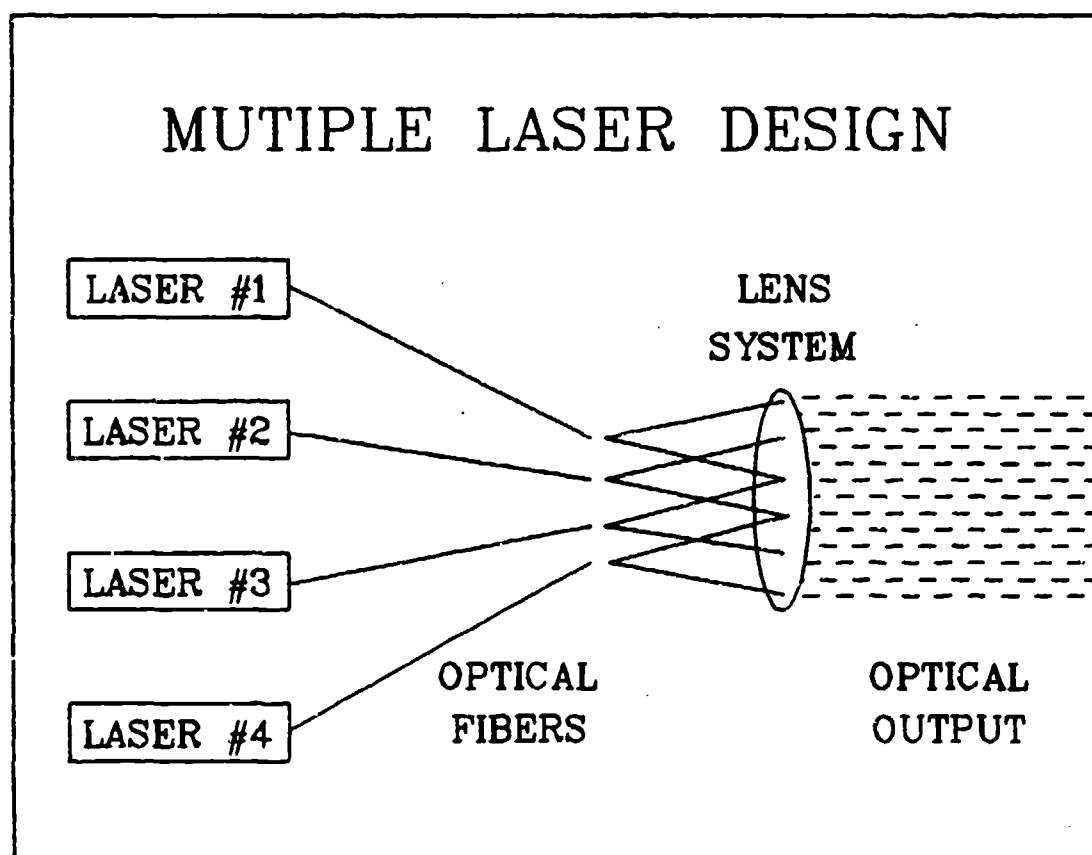


Figure 3: The Multiple Laser Process (4:4)

studies are currently investigating and developing the technology. One important sub-system of most laser stripping removal systems is a robot, a machine programmed for precise control and manipulation of the laser system. Because robots are programmable, the technology is not limited to laser systems, but can be adapted to a wide range of paint removal opportunities.

Robotics

Industrial robots offer many advantages over human labor to perform specific tasks. Robots offer constant process output without fatigue, shift changes, lunch breaks, etc. Robots also offer high degrees of precision, a must for some high technology processes or quality conscience organizations. Consequently, some companies are finding robots as a cost effective alternative to human labor (32:1-2). Since paint removal methods are either labor intensive or employ high technology, robotic process control may be a viable alternative to human labor. But what exactly is a robot and what are the considerations an organization must address before adapting to a robotic environment?

A robot is a programmable, multi-functional device designed to perform specific manufacturing tasks through variable programmed paths. Industrial robots consist of an arm, to which a spray gun, spot welder, or other end effector is affixed; a power source that supplies electrical

or hydraulic power; and a control unit that provides instructions on how to perform the tasks (32:2).

Robots are comprised of two major systems, the central processing system and the operational system. The central processing system processes input data, forming the operational system's guidance signals. The input data is comprised of instructions that define the task to be carried out and measurements concerning the state of the operational unit. The operational system is the physical portion of the robot that receives the signals produced by the central processing system and performs the desired task by transforming energy into mechanical motion (5:9).

The instructions identify the specific sequence of events the robot must perform to complete a given task. A robotic manufacturer will write the instructions so the robot can perform the basic movements the task requires, while the organization employing the robot will further define the instructions (51:95). The instructions are written in a language that either a computer, microprocessor, or programmable controller can interpret (43:10,119).

A robotic paint removal system uses a robot to apply one of the paint removal techniques. The most common robotic system used for aircraft painting and paint removal, a gantry system, uses a framework of steel beams positioned above the aircraft. The beams hold the weight of the robot and provides a full access track for the robot to maneuver

around the aircraft. The system is controlled by an operator who programs a microprocessor, which is the robot's brain. The microprocessor controls the robot's movement, robotic arm, and the method of paint removal. After positioning an aircraft under the framework, the microprocessor automatically fine tunes the robot's position to the position of the aircraft. The system includes such safety features as a collision avoidance system that processes the aircraft's positioning and stops the robotic arm before a collision occurs. Other safety features, such as an emergency stop, allows the operator to override any system (41:7-13).

The manufacturing world realizes the advantages of replacing human workers with robots. A robot consistently obtains a quality product without worker related problems and expenses. However, many companies discover that buying an industrial robot is the least expensive step in automating their factories. Suddenly the companies need experts in computer science, communications, and database technology (11:47). Robotic maintenance is another concern, and is the biggest complaint from robotic users. Since robots are designed and built for unique circumstances, robotic manufacturers routinely fail to include complete maintenance training programs and documentation describing proper maintenance actions (28:71). Robot users are finding ways around this problem by using portable computers and

analytical software that troubleshoots and recommends possible maintenance solutions (39:56-57).

Despite the high costs and maintenance problems associated with robots, manufacturing firms find some applications economically feasible. Determining if a robotic system is economically feasible and should replace manual labor is a detailed procedure. Preliminary data includes evaluating the current production methods in terms of total wages and benefits, costs of materials used, product quality, and environmental considerations. Determining the payback period, defined as the time in which the original investment and operating costs equals the savings earned over the previous production method, is another strong concern. Calculation of the payback period involves the total cost of the robot, operator wages and benefits, and annual robot operation costs minus the annual savings in operation and robot depreciation (32:8-9). The Lockheed Corporation uses an evaluation criteria before automating any of their production areas. Each candidate must show an operational savings; the robotic technology must be low risk; and each applicant must not exceed a three year payback period (47:46). Because of the high initial costs and annual maintenance expenditures, the payback period criteria is the hardest criteria to meet.

Chapter Summary

This chapter presented three paint removal methods; chemical paint stripping, plastic media blasting, and laser paint stripping. The study concentrated on present technology for each of the three methods, plus a supplemental section on robotics. After a brief introduction, each of the three method's histories, technical procedures, and controversial problems were covered. Finally, a robotic system was described, highlighting managerial considerations and implications. The literature developed technical understanding in each of the paint removal methods, and was used as a technical reference during the survey development described in Chapter III. In Chapter III, the methodology used to obtain data to answer the investigative questions will be discussed, as well as the method used to analyze the collected data.

Chapter III. Methodology

Chapter Overview

This chapter presents the methodology used in the data collection and analysis for determining a technical forecast. First, a general description of the methodology is examined, followed by a description of the Delphi's process and use as a technical forecast. After covering the expert selection process, questionnaire development is presented. The statistical concepts pertaining to the Delphi process are examined next, concluding with the process for analyzing the iterations.

General Description

The objective of this study was to determine the steps the aerospace industry will proceed through in the next 15 years or more to obtain a solution to the problems associated with current removal techniques. A literature review combined with a Delphi questionnaire was used to obtain the study's research objective.

The literature review established secondary source background in three paint removal methods and the field of robotics. Chemical stripping was first examined with its history of use, processes, and problems that have evolved since its conception. Next, plastic media blasting's developmental history, controversial substrate damage studies, and application equipment was examined. A method

under intense research, laser stripping, was then investigated for adaptability to the paint removal field. Finally, the robotics field was examined since the use of lasers and other removal processes may require programmable application techniques. The literature review provided both internal and external secondary source knowledge related to the investigative questions (26:136-137).

To answer the investigative questions, a Delphi was used to solicit input from paint removal experts. A Delphi, was determined to be the best method to provide the desired information when used as a technical forecast to investigate the future of paint removal methods (58:2; 42:20-21). The literature review provided fundamental knowledge which, coupled with survey answers from the first Delphi iteration, was used to formulate the second and third round survey measurement questions (26:135).

The Delphi Process

The Delphi method is an iterative opinion questionnaire technique utilizing a group of experts, with anonymous feedback after each iteration. Through several iterations, an optimal consensus is reached. This method was developed in the late 1940s at the Rand Corporation in an attempt to have experts voice their opinions free of any dominant individual or majority opinion (58:2).

There are two underlying assumptions that the designer must secure to make any Delphi successful. First, the

designer must ensure that the experts participating in the research are extremely knowledgeable and experienced in their respective field by investigating demographic information (21:140). Second, since the combination of knowledge and experience obtained from several people is more accurate than one individual's experience or knowledge, the designer must maintain at least the minimum number of expert participation (0018:6-10). Thus, it is the designer's responsibility to insure that the experts participating in the research are indeed professional sources and there is an adequate number of experts participating in the Delphi (0017:140).

The number of participating experts has a dramatic effect on the Delphi's reliability. In general, one individual's answer in a Delphi is less reliable than two individuals'. Likewise, two individuals opinions are less reliable than three experts. This philosophy continues in a linear fashion until the group size is eleven, where the reliability increases at a much lower rate. Thus, the Delphi is considered reliable if eleven or more experts participate throughout the research (22:6-10).

The Delphi process is an adaptable concept that is easily employed; however, the method is by no means without disadvantages. Problems with a Delphi include insufficient reliability, ambiguous questions, difficulty in assessing the degree of expertise, and unexpected circumstances (46:189). These problems arise when the designer does not

carefully consider the potential situations involved in carrying out the exercise. Some of the common reasons for poor results are:

1. Poor techniques of summarizing and presenting the group response and ensuring common interpretations of the evaluation scales.
2. Ignoring and not exploring disagreements. This encourages some participants to drop out, thus generating an artificial consensus.
3. Underestimating the demanding nature of a Delphi.
4. Imposing monitor views and preconceptions of a problem upon the participating group (44:6).

In any one Delphi application it is impossible to eliminate all of the problems mentioned. It is the task of the designer to minimize these problems and communicate effectively the goals of the Delphi to the participants (44:6).

The Delphi process can be used to develop a technological forecast when used to predict technical information (21:142; 44:247-253). An accurate forecasting tool is vital to the success of any business, which can be used for a variety of circumstances such as projecting sales, economic growth, and technical breakthroughs. Forecasting is divided into two major groups, quantitative and qualitative. Quantitative methods are generally used for short period applications of one year or less, where the environment is stable and quantitative historical data is available. Qualitative forecasting methods are primarily used for long range forecasting of one year or longer (21:140). Qualitative forecasts, such as determining the

future of paint removal methods with the Delphi process, is considered a technological forecast (44:247-253; 42:20-21).

Expert Selection

One of the first steps in performing a Delphi involves the expert group selection. A number of parameters can distinguish experts from non-experts such as educational level, professional training, experience, and specific skills pertinent to the Delphi study (58:4-5). One general approach uses the perceived expert's reputation, recommendations by peers, and authors of published articles as selection references. However, the designer should also be careful to include a broad professional representation if the field includes different philosophies or operating principles (57:193).

Once a group of potential experts is identified, it is important to select the participating professional group randomly so as not to induce bias (22:12). A method used for identifying professionals randomly in one field may not work in another situation, therefore, the Delphi designer must review the particular circumstances and formulate the most appropriate expert criteria (44:6-7). In this study, the experts were randomly chosen through a stratified sampling technique (26:306-312).

To ensure an unbiased outcome, it is important to be sure that their involvement in the Delphi is sincere. This is accomplished by explaining to the candidates the

experiment intentions and asking if they are interested in participating. Compensation can be discussed, but the designer should not use it as a luring tool (44:210-211).

The aircraft paint removal field includes individuals with many different technical education degrees and related experience levels. It was virtually impossible to list all the desired expert's education and experience levels, because each aircraft paint removal method requires a different background. To represent all of the methods, the study included experts who had a broad knowledge of existing and researched methods. Furthermore, the study did not include experts who worked solely for any one organization such as DOD services, a large airline, or a small research business, but included experts from each of the organizations. This allowed the group to function with the depth of technical knowledge needed to form a broadened forecast, avoiding a narrow train of thought possibly influenced by individuals working for one specific organization.

The 1988 Advanced Coatings Removal conference gathered corrosion control experts together, representing a variety of paint stripping technologies. The conference included 208 technical representatives from the Department of Defense, Federal Aviation Administration, and civilian industries. The conference was conducted by 33 specialists who presented their latest paint removal findings (37:1-3).

The 33 specialists conducting the conference represented a potential expert group needed for a successful Delphi.

It was reasonably assumed that the 33 individuals were experienced in their particular paint removal field, authors of published articles, and had a broad enough technical education level to understand related paint removal topics (57:193). To justify sincere involvement, letters explaining the Delphi method and the experiment's intentions were mailed to each of the 33 individuals requesting their involvement in the research (Appendix A). Historically, one individual out of three contacted initially participates in the research, but the return response exceeded the historical rate with 25 positive replies (44:211).

Questionnaire Development

The Delphi process is extremely adaptive, and has no set rules governing the Delphi's initial questionnaire format. One possible method would base the questionnaire on a thorough literature review and systematically sample the applicable items (58:4). Another style would send a vague description of the forecasting problem to the identified experts for their ideas on the leading problem areas. The initial questionnaire is then developed from the popular problem areas (21:140).

Because of the vast number of possible paint removal technologies, a questionnaire developed from a literature review would induce the designer's bias though the selected

topics. Furthermore, current research and development of possible methods are unpublished, and excluded from the literature review. Therefore, the first Delphi iteration asked the experts to provide their thoughts on the investigative questions and requested individual demographic information (Appendix B). The first iteration provided the primary data which was used to develop the second and third iterations' measurement questions (26:22, 200). The first iteration also established demographic information on each expert (Appendix C). Both the investigative and demographic questions were instrument tested for content and clarity (26:206).

The second iteration measurement questions were developed from the first iteration's common responses (Appendix B) (21:140). A common response was established when over half of the replies to a given investigative question referenced a specific technology or problem. The literature review provided a secondary source of fundamental background information, allowing the designer to interpret unclear responses from the first iteration (58:4).

The designer used extreme caution when wording questions to communicate distinctly and avoid irrelevant answers to ambiguous, unclear questions. To communicate clear meanings, the questions used throughout iterations two and three included qualification of terms and background conditions when appropriate (Appendix D). If these explanations were not included, the experts might have

projected many different interpretations leading to non-comparable responses (26:207-222; 58:6).

The experts were asked to indicate their responses to each measurement question through the ordinal scale following each question. Three different ordinal scales were developed through semantic differentiation and used throughout the iteration (26:261-265). Each scale was differentiated through bipolar measurement parameters that offered the expert the appropriate values or ranges for responses to a given measurement question. Each scale was designed not to reflect inappropriate measurement parameters, thereby influencing the outcome with lack of credibility or ambiguous question values (35:2-3).

Therefore, testing each question's measurement system relevance on a number of qualified individuals who are not associated with the expert group is an important step (44:226). The measurement questions and ordinal scale values were instrument tested for content, clarity, and appropriate values (26:206).

All three Delphi iterations were conducted through written communication, which allowed anonymous questionnaire responses. This also permitted:

1. many widely separated experts to participate without travel or time inconvenience.
2. allowed the group to focus on the major developments very quickly and discuss only those prospects in detail (44:195).

However, there were a couple of drawbacks to the written communication approach:

1. the time expiring between iterations.
2. ambiguous questions that required further explanation (57:194).

Furthermore, the designer attempted to ensure unbiased results by not matching responses with the respondents when analyzing iteration responses (57:191).

Statistical Concepts

The Delphi process uses an iterative questionnaire approach to evaluate agreement between experts on a particular subject, with their agreement measured statistically through central tendency characteristics. Central tendency for ordinal scale measurements are represented by the median and the mode, with the mode more appropriate for determining a consensus among the experts (26:88-89). The mode is defined as the set of measurements that occur with the highest frequency (52:32). A consensus on any given question was determined when 70% of the replies constituted the mode measurement.

Because the experts' answers revealed a spread of responses, inter-quartile ranges were computed for each question. The inter-quartile range indicates the middle 50% of the responses, with the median representing the 50th percentile (21:140; 42:21). A truncated wedge diagram was used to indicate the inter-quartile ranges. The truncated portions indicate the 25th and 75th percentiles, respectively, while the rise in the center of the wedge reveals the median. Unlike a histogram, no significance is

attached to the vertical height of the truncated wedge diagram (40:231).

With the Delphi using an ordinal measurement scale, the results were statistically analyzed through non-parametric testing (26:88-89). Questions failing to achieve a consensus by the second iteration were examined for response changes or trends in iteration results to determine if the expert population collectively changed their responses between the second and the third iteration. Because each iteration was dependent upon the previous, a non-parametric test that identifies a population shift was required. This test was the Wilcoxon Signed-Rank test (52:199-200). The test procedures were:

Null Hypothesis:

The distribution of differences between each iteration is symmetric around the second (baseline) iteration results.

Alternative Hypothesis:

The differences are not symmetric around the second iteration results (52:199-200).

Test Statistic:

The two tailed p-value is computed by the software package Statistix.

Rejection Region:

For a specified value of alpha, reject the Null Hypothesis if the p-value is less than the specified alpha value (61:6.7-6.8).

The micro-computer statistical software package "Statistix" was used to calculate the Wilcoxon Signed-Rank test, with the results given in Appendix F. At a specified alpha value of .025, the rejection region is indicated by any two tailed p-value less than the specified alpha value.

Note the program tests the experts' answers where a change is indicated between the two iterations. This is indicated by the number of cases included in the output for each question. Additionally, the program only calculates the Wilcoxon's Signed Rank Test when three or more experts change their response from the second iteration (61:6.7-6.8).

Analysis Method

The Delphi procedure formulates group opinion through questionnaire iteration and controlled feedback. Analysis of the second iteration revealed those questions which had achieved consensus. The third iteration repeated the second iteration's questions which failed to reach a consensus, along with the mode measurement and the individual's answer for each question. The experts were asked to reconsider their response in view of the added information. If the expert strongly disagreed with the mode, the expert was asked to give explicit reasons why their estimate differed significantly from the group's modal response (21:141; 13:4-6). The second and third iteration steps are generally associated with the convergence with a smaller spread of answers on the second and third rounds, and increased accuracy on the questions for which answers change. Historically, the majority of answers do not change with each iteration (14:1).

The questions achieving consensus on either the second or the third round was considered the forecasted answer for the given measurement question. Questions not obtaining consensus used the median indicated in the third round as representing the group's forecasted answer (42:22). The forecasted answer was further analyzed for ambiguity, with an ambiguous answer indicated by a long inter-quartile range (40:231,233).

Chapter Summary

This chapter presented the methodology used in the data collection and analysis for determining a technical forecast. First, a general description of the methodology was examined, followed by a description of the Delphi's process and use as a technological forecast. After inspecting the expert selection process, questionnaire development was presented. The statistical concepts about the Delphi process were proposed next, concluding with the process for analyzing the iterations.

Chapter IV. Analysis and Findings

Chapter Overview

This chapter analyzes the data obtained through the Delphi iterations. First, the data collection process is reconstructed highlighting the time frames and expert participation during each round. Next, the overall Delphi results are discussed. Finally, each of the investigative questions are analyzed through the related measurement questions. The measurement questions were analyzed using the procedures outlined in Chapter III, with the results supplied in Appendixes E and F. The findings concluded for each investigative question are then presented, further defining the relationship between each measurement question and the investigative question.

Data Collection Process

Round One. The first Delphi round consisting of 25 surveys was mailed on December 14, 1988. Due to the holidays and the time required to answer the open ended investigative questions, the experts were asked to complete and return the survey as soon as practical. The first iteration was terminated on January 16, 1989 with 17 of the 25 surveys received. The remaining 8 experts were contacted to ensure they did receive the first iteration, and questioned if they still wanted to participate. When contacted, 3 experts expressed they underestimated the time

involved in completing the survey and requested to be excluded from the study. The remaining 5 stated they would complete the survey promptly; however, no further surveys were received. Thus, a total of 17 surveys were used for the research.

Table 2: Panel Demographics

Panel Demographics				
Res. #	Ed. Level	Current Position/Rank	Work Experience	Total Work Experience
1	B.S.	GM-14	Chemical Stripping	30 yrs
2	M.B.A.	GS-11	PMB, Chemical Stripping	10 yrs
3	M.B.A.	C.E.O.	PMB, Chemical Stripping	5 yrs
4	PhD.	Group Leader	Variety of methods used on aircraft, boats, and equipment	3 yrs
5	M.S.	GM-13	PMB, Chemical Stripping	6 yrs
6	PhD.	Owner, PMB Consulting firm	PMB, Chemical and Laser Stripping, others	23 yrs
7	B.S.	Project Engineer, 0-2	PMB, Chemical and Laser Stripping, others	3 yrs
8	M.S.	GS-12	PMB, Chemical and Laser Stripping, others	6 yrs
9	B.S.	Process Engineer, GS-11	PMB, Chemical Stripping	2 yrs
10	B.S.	Development Engineer	PMB, CO2 Dry Pellets	2 yrs
11	B.S.	Industrial Engineer	PMB, Chemical and Laser Stripping, others	3 yrs
12	PhD.	Research Scientist	PMB, Chemical and Laser Stripping, others	5 yrs
13	M.S.	Vice President General Manager	PMB, Chemical and Laser Stripping, others	15 yrs
14	B.S.	Senior Research Engineer	PMB, Chemical Stripping, others	17 yrs
15	B.S.	Vice President Marketing	PMB	4 yrs
16	M.S.	DOD Program Manager	Laser Stripping	1.5 yrs
17	M.B.A.	Senior Material Engineer	PMB, Chemical Stripping, others	20 yrs

During this round the panels' demographics were established (Table 2 and Appendix C) and the specific concerns within investigative question identified (Appendix B). As mentioned in Chapter III, measurement questions were identified when 9 or more experts communicated similar concerns for each investigative question. A total of 39 questions were used to further examine the investigative questions (Appendix D).

Round Two. After the measurement questions were identified, the second Delphi round was mailed on March 3, 1989. The experts were asked to complete the survey as soon as possible, with all 17 responses received by March 30, 1989. The responses given by the experts for round two are displayed in Appendix E.

During the analysis of round two, not all experts responded to each question using the ordinal scale. However, some of the experts did explain that either they did not have the background to competently answer the question or remarked they were undecided on the appropriate answer.

As previously discussed in Chapter III, the modal response was used to determine group consensus. A consensus was established when 70% of the panel agreed on the same response; thus, when 12 respondents agreed, a consensus was obtained.

Round Three. After the results from the second round were statistically determined, the same 39 questions from

round two were resubmitted to each expert, but with additional information provided from the second round's results. First, the mode and range were provided for each question. Second, comments made by the experts during the second round were also provided. Lastly, the ordinal response given by the particular respondent for each answer in round two was indicated. This allowed the respondent to compare their original answer to the modal response and other individual responses made by the groups' members.

Round three was mailed on May 5, 1989. The round was terminated on June 9, 1989, after 16 responses were received. After receiving 14 responses, the remaining 3 experts were contacted to ensure they received the survey. One of the experts did not want to change any answers from the second round, and stated the designer should use his second round answers as his third round response. Of the remaining two experts, one response was promptly mailed while the other was never received. Responses given by the panel for round three are shown in Appendix E.

Overall Delphi Results

The Delphi iterations produced a group consensus on six of the 39 questions, or 16%. This statistic indicates the experts found it difficult to agree, as a group, on specific considerations affecting the paint removal domain. The experts did collectively acquire median and inter-quartile responses that can be used to forecast removal methods.

On questions not receiving consensus on the second round, the Wilcoxon Signed Rank Test was performed. This test was used to show a shift in the groups collective response, with the results indicated in Appendix F. With only one question reflecting a distribution shift when alpha was defined at .025, and only one additional question indicating a shift when alpha was .05, it can be assumed that the additional information provided in the third round had little effect on changing the groups' collective responses. Consequently, supplementary iterations would be pointless in trying to obtain further consensus on any of the questions.

Investigative Question #1 Analysis

The first investigative question was to determine what paint removal methods are likely to suit future paint removal needs. The measurement questions related to the investigative question #1 are the first 14 questions shown in Table 3. During the Delphi the experts obtained consensus on question #9, agreeing that plastic media blasting will be used in the future for complete aircraft paint stripping. However, the panel was unable to achieve consensus on any of the other measurement questions regarding investigative question #1.

Although the experts failed to reach consensus on other measurement questions, they were able to collectively make some strong predictions. As depicted by the inter-quartile

Table 3: Investigative Question #1 Measurement Questions

Investigative Question #1 Measurement Questions

- #1) The logical iterations of stripping methods will evolve from chemical stripping to plastic media blast to laser stripping.
 - #2) How will chemical stripping will be used in the future?
 - #3) Chemical stripping will cease to be used for exterior airframe surface paint removal in how many years?
 - #4) Chemical stripping will continue to be used because of its' non-damaging effects on certain substrates.
 - #5) Plastic media blasting will be the interim method of choice for exterior airframe surface paint removal, but only until another removal method is perfected.
 - #6) Plastic media blasting will cease to be used for exterior airframe surface paint removal in how many years?
 - #7) Plastic media blasting will not be the predominant method because of its' effects on certain substrates.
 - #8) Plastic media blasting will become the predominant paint removal method for exterior airframe surface stripping in how many years?
 - #9) How will plastic media blasting will be used in the future?
 - #10) Laser stripping will become the predominant exterior airframe surface paint removal method in how many years?
 - #11) Laser stripping will not become the predominant exterior airframe surface paint removal method because of technical difficulties.
 - #12) Laser stripping use will not become the predominant exterior airframe surface paint removal method because of its' high equipment costs.
 - #13) How will laser stripping will be used in the future?
 - #14) Another method (excluding chemical, plastic media blasting, and laser stripping) will become the predominant exterior airframe surface paint removal method in the future.
-

range in question #3 of Figure 4, the experts forecasted chemical stripping will cease to be used for exterior airframe surface paint removal in 4 years or less. In question #6 of Figure 4, the panel predicted if PMB is adopted for exterior airframe paint removal, PMB will never be replaced. This finding is weakened by the large inter-quartile range that starts at 12 years and spans to never.

Question #6 was also identified as one of the measurement question in the Wilcoxon signed rank test (Appendix F) as having a distribution shift. Between the second and third iteration of question #6, the panel shifted

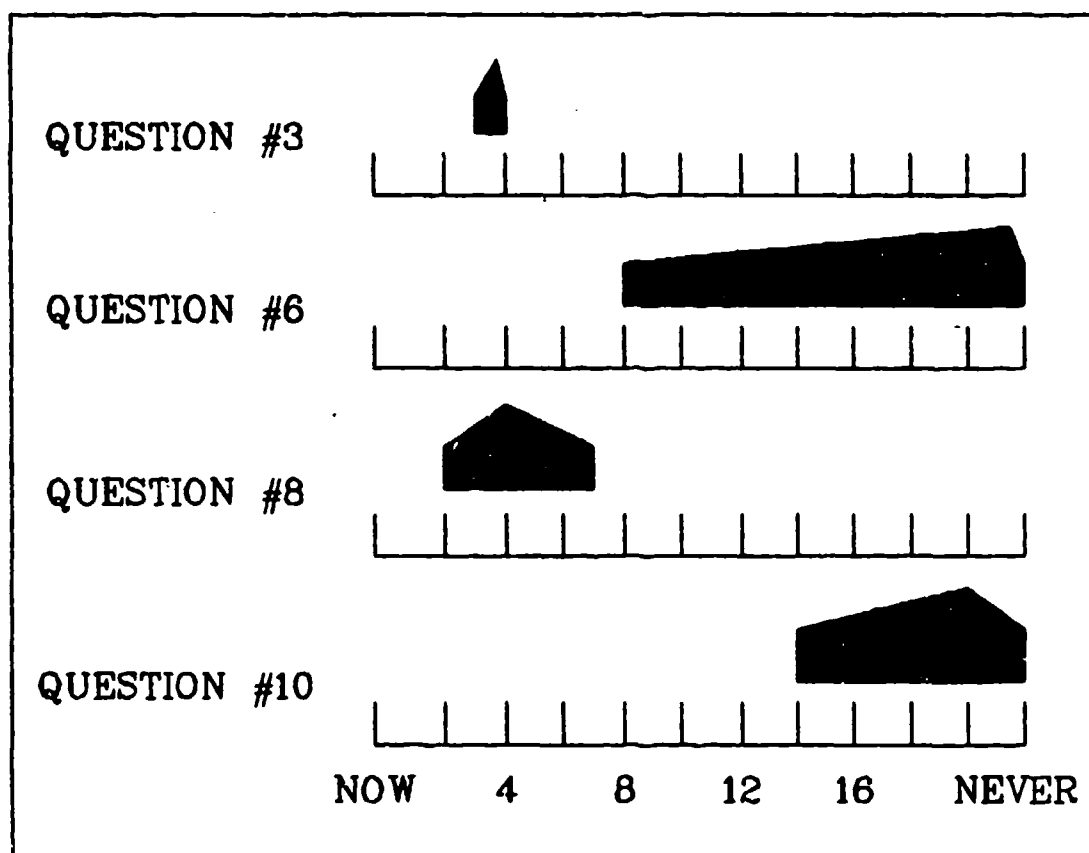


Figure 4: Investigative Question #1 Inter-Quartile Ranges

their answers from 56% of the experts responding plastic media blasting will never cease to be used for exterior airframe paint removal, to an 86% response in the third round.

To further define plastic media blasting's use, the experts projected the method will be used for complete aircraft paint stripping in four years, as shown in question #8 of Figure 4. The panel was asked to predict when laser stripping would become the predominant exterior airframe paint remover, as referenced in question #10 of Figure 4. The inter-quartile range spanned from 14 years to never,

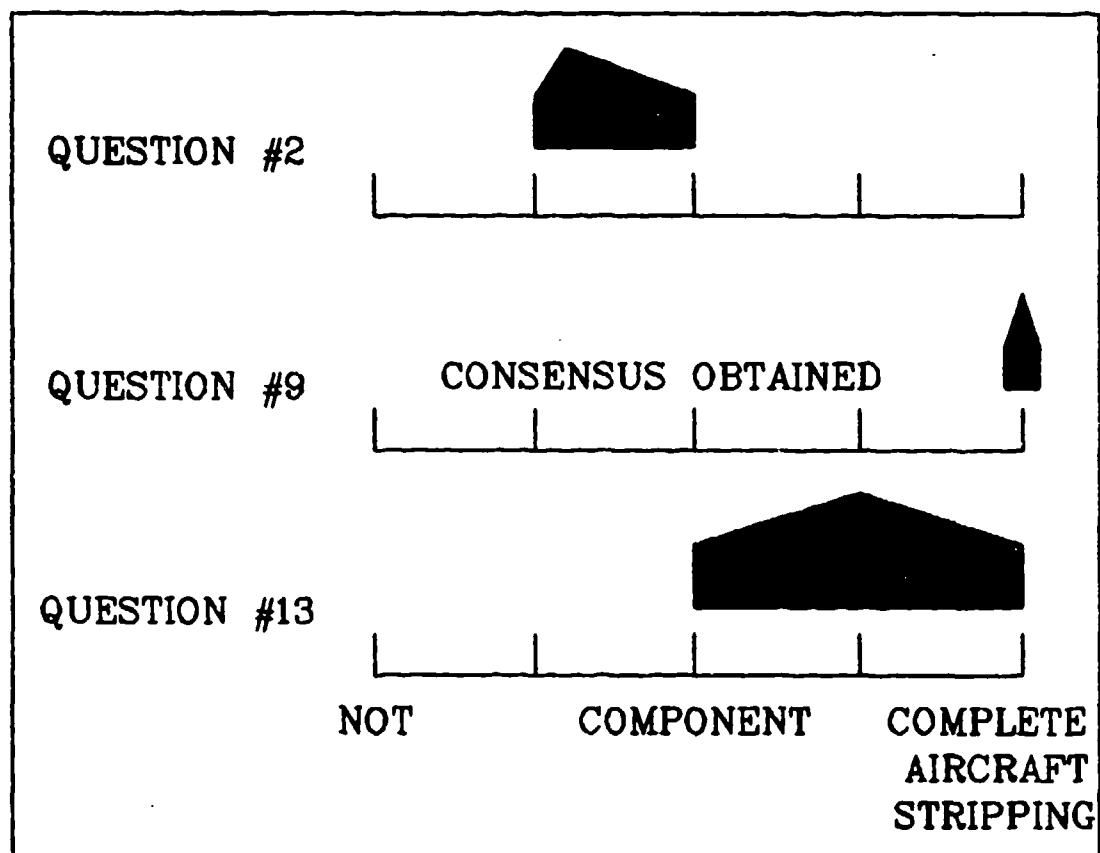


Figure 5: Investigative Question #1 Inter-Quartile Ranges

with the forecast resulting in 20 years. During the second and third iterations of question #10, a shift of opinion was detected by the Wilcoxon Signed Rank Test ($\alpha=.05$). During the second round, 59% of the panelists responded 14 years to never while the responses shifted to 75% during the third round.

The panel decided that when chemical paint stripping is used for paint removal, it will be on components less than 18 cubic inches, as depicted in question #2 of Figure 5. The experts did reach a consensus that plastic media blasting will be used in the future for complete aircraft stripping, as depicted in question #9 of Figure 5. Laser stripping's future use will be for large items, such as wings, rudders, and complete aircraft stripping, as portrayed in question #13 of Figure 5.

When asked to predict if the paint removal process will evolve from chemical stripping to PMB, and finally laser, the panel had responded neutrally, as depicted in question #1 of Figure 6. Individual comments observed problems with lasers, and mentioned the possibility of another removal method besides laser stripping.

As uncovered in the literature review, the panel responded that one of the problems with chemical stripping is its damaging effects on certain substrates, as seen in question #4 of Figure 6. However, they also verbally stated that chemical stripping will continue to be used when other methods are unacceptable.

The experts had mixed responses concerning if PMB will be replaced by another method, as depicted in question #5 of Figure 5. Further supporting the panel's prediction that plastic media blasting will be the method of choice, the experts disagreed with the statement that PMB will not be the predominant removal method because of its' effects on certain substrates, as shown by question #7 of Figure 6.

Out of all the methods discussed, laser stripping had the widest range of answers, thus, offering the broadest response interpretations. As shown in question #11 of Figure 7, the panel agreed that technical difficulties will

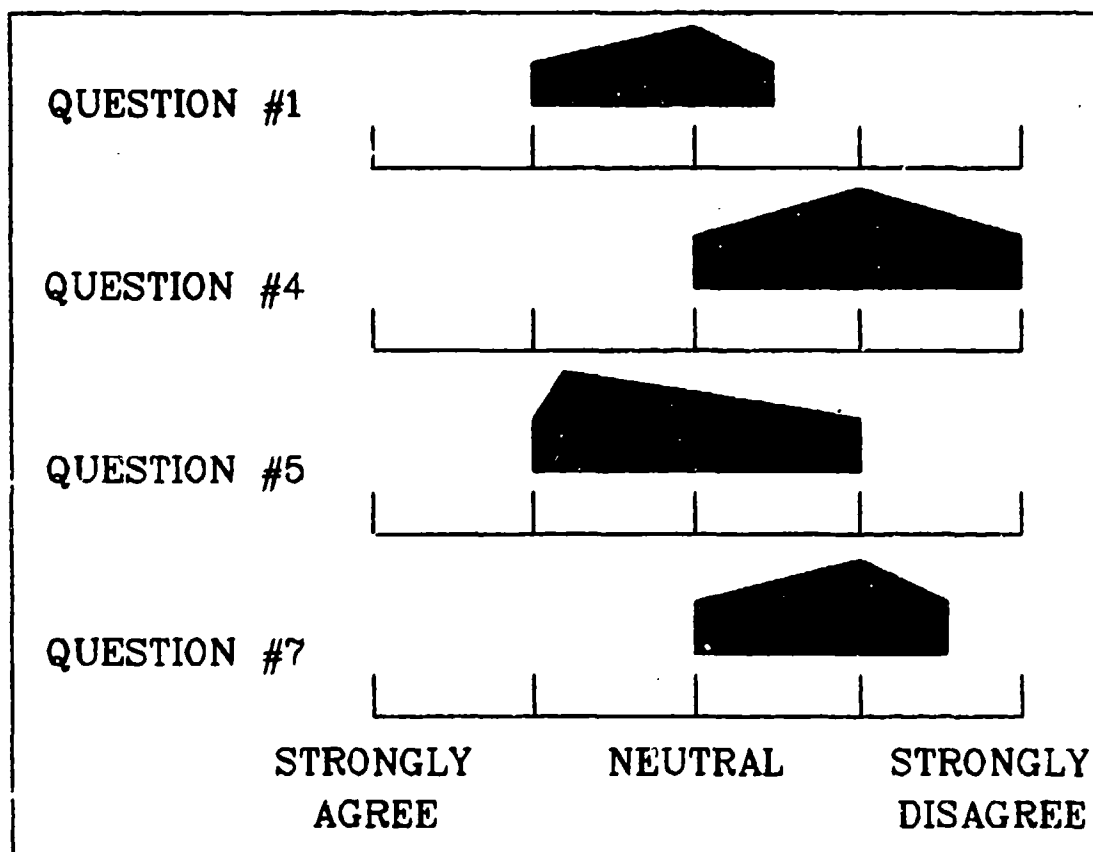


Figure 6: Investigative Question #1 Inter-Quartile Ranges

prevent laser stripping from being the predominant exterior surface paint remover. The panel agreed that high equipment costs will be a major hurdle for successful laser stripping, but not strongly as represented in question #12 of Figure 7.

The experts also indicated a neutral response that any other known method of paint removal, excluding chemical, PMB, and laser stripping, will become the predominant exterior airframe surface paint removal method, as represented in question #14 of Figure 7.

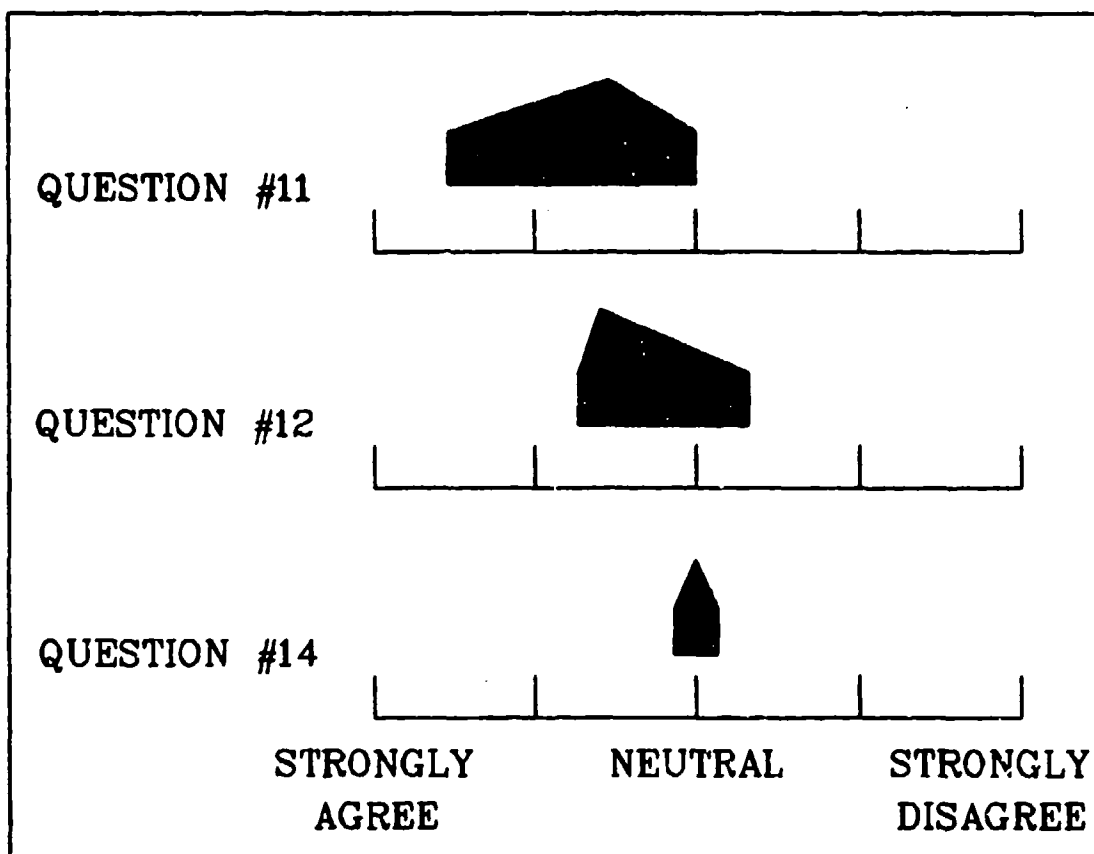


Figure 7: Investigative Question #1 Inter-Quartile Ranges

Findings For Investigative Question #1

Consistent with the literature review, the panel affirmed the problems associated with chemical stripping. Although a consensus was not obtained on any chemical stripping related issues, the inter-quartile ranges revealed strong trends in agreement. The experts responded that within 4 years chemical stripping will not be used for exterior airframe paint removal, and its use will be confined to components 18 inches or less in diameter. In turn, chemical stripping will be replaced by PMB for exterior paint removal.

The forecast also exhibited that PMB will be the predominant exterior paint removal method, and this will happen within 2 to 6 years. The literature review noted specific problems using PMB on certain substrates, with the panel responding that PMB will not have damaging effects. The panel further forecasted that PMB will never be replaced as the premier removal method, a notion that correlates with the mixed responses concerning the paint removal evolution from chemical to PMB, and finally laser stripping.

As noted in the literature review, laser stripping is in its infancy. This fact is further supported by the panel's scattered laser stripping responses; however, some inter-quartile ranges were prominent. First, technical difficulties and high equipment expense are the major issues confronting laser stripping. If adopted, laser stripping will be used for stripping large components, such as

rudders, wings, and complete exterior airframes.

Furthermore, the panel had mixed responses when and if laser stripping would be used.

In general, the panel concluded that chemical stripping will cease to be used for complete exterior airframe paint removal within 4 years, and will be replaced by PMB. A large question mark looms if PMB will ever be replaced by another method in the next 15 years.

Investigative Question #2 Analysis

The second investigative question was to determine what research and development efforts will the new methods require. The measurement questions related to the investigative question #2 are questions 15 through 22 as shown in Table 4 and in Appendix D. During the Delphi the experts obtained consensus on question #21, agreeing that robotic technology must develop concurrently with laser technology for laser stripping to be successful. The panel was unable to achieve consensus on any of the other measurement questions concerning investigative question #2.

Because of the current and scheduled research and development in PMB, the experts were asked if PMB is fully developed. The panel strongly disagreed with the statement that PMB is fully developed and requires no further research, as depicted in question #15 of Figure 8.

As uncovered in the literature review, laser paint removal systems are frequently associated with robotic

application systems. Sequentially, the experts did achieve consensus on question #21 of Figure 8, strongly agreeing that robotic technology must be developed concurrently with laser technology for successful laser stripping.

Further defining PMB's development, questions #16 and #17 of Figure 9 projected that the PMB process will become optimized for exterior airframe paint removal in 2 years, and consequently the parameters will be optimized in 2 years

Table 4: Investigative Question #2 Measurement Questions

Investigative Question #2 Measurement Questions

#15) Plastic media blasting is fully developed and requires no future research.

#16) The plastic media used for the plastic media blasting process will become optimized for exterior airframe surface paint removal needs in how many years?

#17) Plastic media blasting parameters will become optimized for exterior airframe surface paint removal needs in how many years?

#18) Plastic media blasting will become suitable for use on composites in how many years?

#19) Laser stripping parameters will become optimized for exterior airframe surface paint removal needs in how many years?

#20) Laser stripping will become suitable for use on composites in how many years?

#21) Robotic technology must develop concurrently with laser technology for laser stripping to work.

#22) Robotic applications appropriate for a paint stripping environment will become developed and in use with either PMB, laser or another method for exterior airframe paint removal in how many years?

for the same application. As a side note, some commented that a method can never be optimized; there's always room for improvement.

The literature review revealed a controversy evolving PMB and its use on certain substrates, primarily composites. The panel replied that PMB will be suitable for composite substrate stripping in 2 years, as represented in question #18 of Figure 9. The experts commented that the process is suitable now, under controlled conditions and skilled operators.

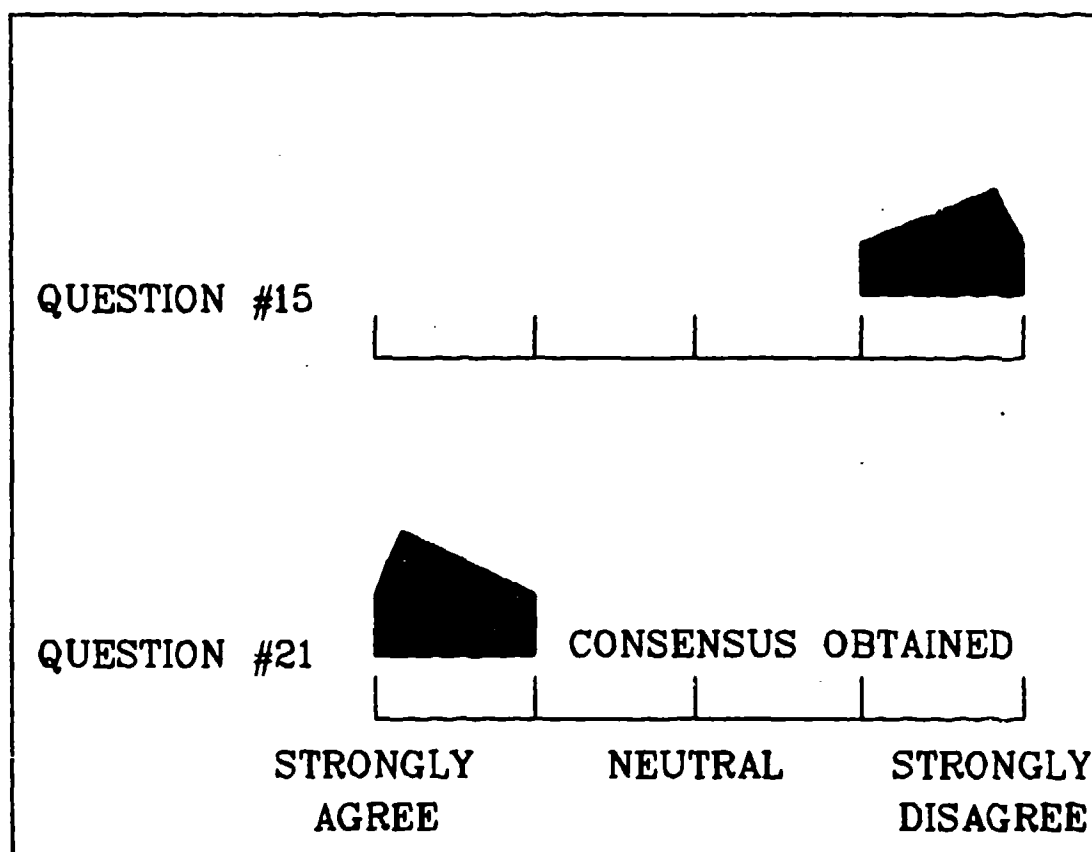


Figure 8: Investigative Question #2 Inter-Quartile Ranges

Laser stripping continued to be a controversial subject between the experts. The range of answers were wide spread; again, offering a broad interpretation of results. As displayed in question #19 of Figure 10, the experts responded that laser stripping's parameters will become optimized for exterior airframe paint removal in 10 years. When asked about laser stripping use on composites, the projections were similar with the median response of 12 years, as depicted in question #20 of Figure 10.

As mentioned in the literature review, robotic technology can be used with other paint removal methods

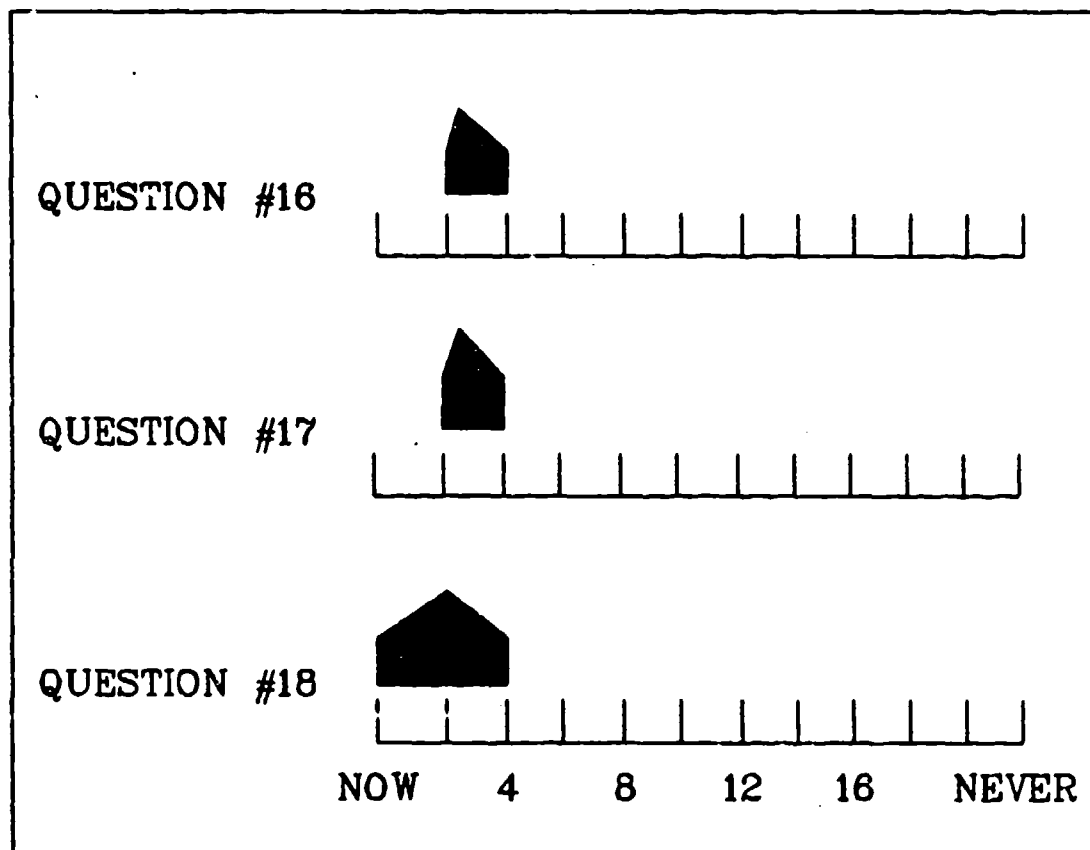


Figure 9: Investigative Question #2 Inter-Quartile Ranges

other than laser stripping. The panel forecasted that in 4 years robotic technology will be developed for removal methods other than laser stripping, as referenced in question #22 of Figure 10.

Findings For Investigative Question #2.

Definitions concerning the PMB process are an important consideration when analyzing the results applicable to PMB's research and development. The panel strongly disagreed that PMB requires further research; however, it will take up to 4 more years before the process and its parameters are

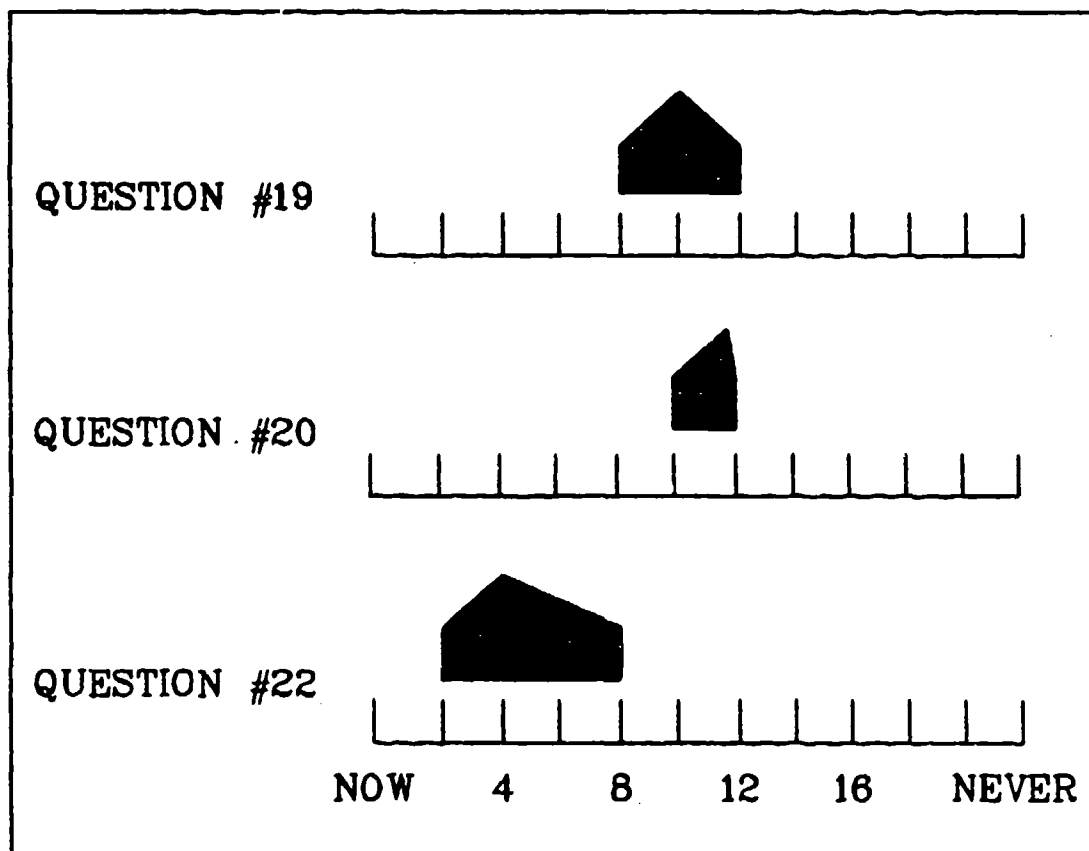


Figure 10: Investigative Question #2 Inter-Quartile Ranges

optimized for exterior airframe paint removal. PMB can be safely used on composites in 2 years; however, some experts commented the method is suitable now when applied under controlled conditions and operated by skilled technicians.

The experts responded that laser technology research and development is at least 10 years away from being approachable for exterior airframe paint stripping. Consequently, the panel projected laser stripping can be used on composite substrates in 12 years.

The panel did agree that laser stripping and robotic technology must be developed together for a successful paint stripping system. Robotic technology is adaptable to removal methods other than laser stripping. The panel forecasted in 4 years the two technologies will combine.

In general, PMB technology is developed for successful stripping. PMB's process and parameters for exterior airframe paint removal or composite substrate is 2 years away from being optimized. Laser stripping questionable usage depends on research and development. The panel projected the technology is 10 years away from becoming optimized, but its success depends on an integrated robotic application system. As far as other removal methods, robotic technology will be adapted in 4 years.

Investigative Question #3 Analysis

The third investigative question was to determine what worker safety considerations will impact future paint

removal methods. The measurement questions related to the investigative question #3 are questions 23 through 28, shown in Table 5 and Appendix D. During the Delphi the experts achieved consensus on question #23, agreeing that PMB worker safety equipment that environmentally protects the worker is available now. However, the panel was unable to achieve consensus on any of the other measurement questions.

Because of chemical stripping's toxic chemicals, worker environment issues is a vital concern. As depicted in question #24 of Figure 11, the panel exhibited a large

Table 5: Investigative Question #3 Measurement Questions

Investigative Question #3 Measurement Questions

#23) Worker safety equipment that environmentally protects the worker while applying chemical stripping procedures will become available in how many years?

#24) Chemical stripping poses a serious threat to the worker's health. The only way to use chemical stripping safely is to remove the worker completely from the stripping environment.

#25) Plastic media blasting worker safety equipment that environmentally protects the worker will become available in how many years?

#26) Plastic media blasting must have specific facilities built that safely collects dust and paint chips.

#27) Laser beams are harmful to anyone in the stripping area. The technology that reduces the beams' harmful effect to a safe level while successfully performing stripping operations will become available in how many years?

#28) Laser stripping must have dedicated facilities precisely built for the laser to safely strip an exterior airframe surface.

inter-quartile range from strongly agree to disagree when confronted with the statement: the only way to use chemical stripping safely is to remove the worker completely from the stripping environment.

Since the PMB process includes retrieval and separation of paint chips and plastic dust, the experts strongly agreed that PMB must have specific facilities built that accommodates the PMB process, as depicted by question #26 in Figure 11. Furthermore, the panel strongly agreed laser stripping must have dedicated facilities for safe exterior airframe paint removal, as displayed in question #28 of

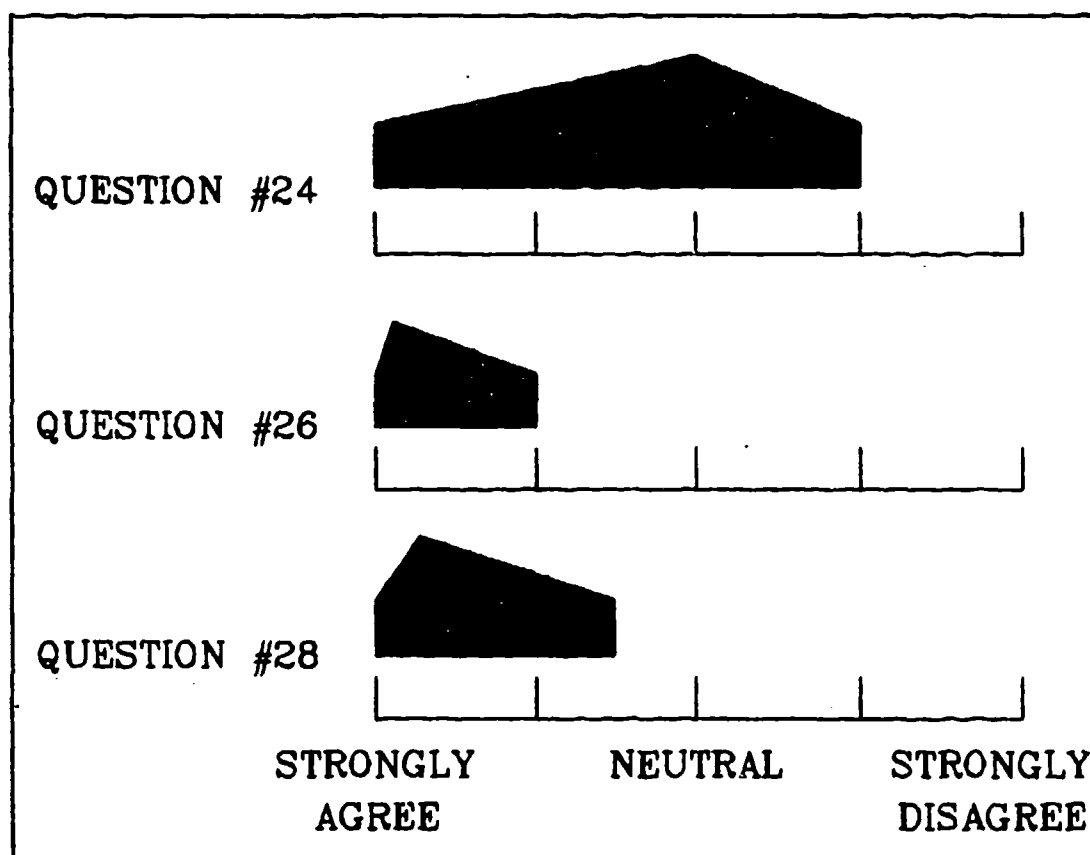


Figure 11: Investigative Question #3 Inter-Quartile Ranges

Figure 11. In regard to the facility, some experts commented that existing facilities can be modified for laser stripping.

As depicted by question 23 of Figure 12, the experts obtained consensus responding the technology that environmentally protects the worker while applying chemical stripping procedures is available now. Individual comments made by the experts surfaced reports that even though the equipment is available today, workers operate it improperly and induce environment related injuries.

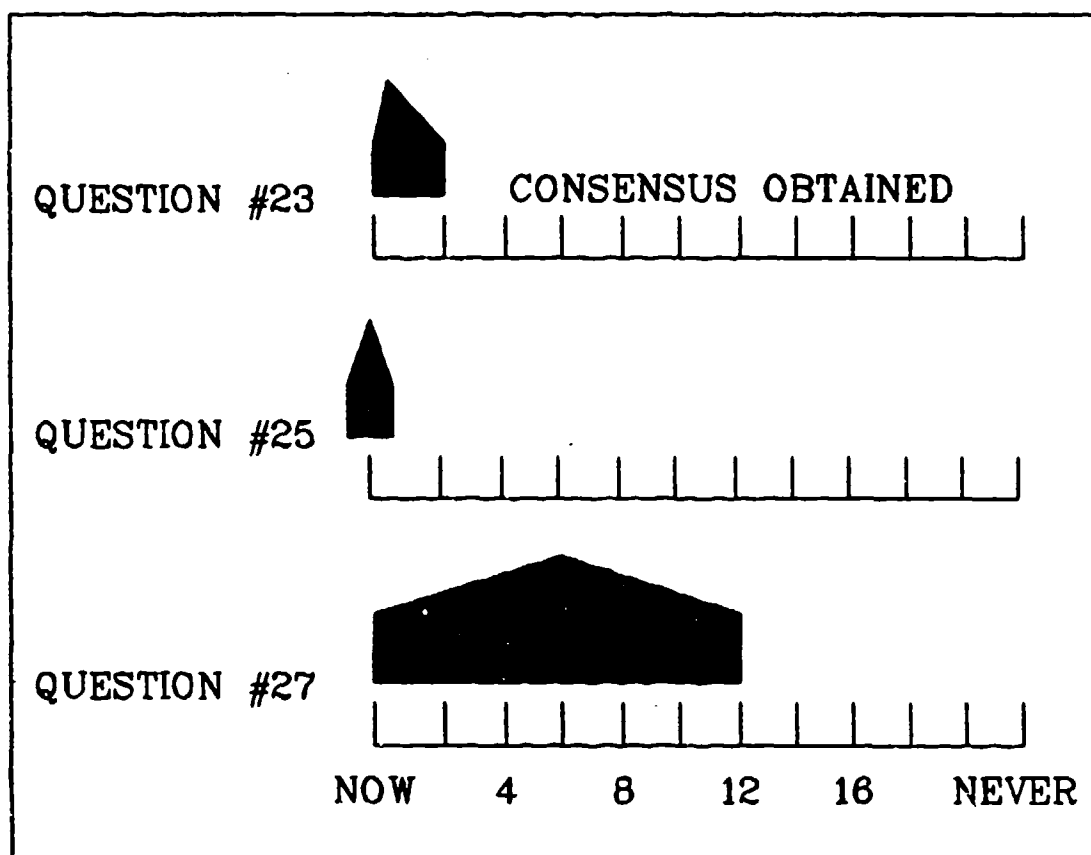


Figure 12: Investigative Question #3 Inter-Quartile Ranges

It was agreed upon that PMB worker safety equipment that environmentally protects the worker is available now, as represented by question #25 in Figure 12. As shown in question #27 of Figure 12, the experts were in disagreement on how long it would take the laser beam to be environmentally safe while performing stripping operations, with the inter-quartile range spanning from now to 12 years.

Findings For Investigative Question #3.

As mentioned in the literature review, the environment the worker operates within while performing chemical stripping practices is hostile. The experts indicated the technology that environmentally protects the worker is available today. Despite the hostile environment, the panel neither agreed or disagreed with removing the worker from the chemical stripping environment.

The equipment that environmentally protects the worker while performing PMB operations is available now. The panel also strongly agreed that dedicated facilities must be utilized to accommodate the environmental impacts of plastic dust and paint chip extraction from the used media. It was further strongly agreed that dedicated facilities for laser stripping must also be employed for safe operations.

In general, the equipment that protects the worker while performing either chemical stripping or PMB procedures are available now. However, in the case of chemical stripping, the equipment's effectiveness depends on its

proper usage. To employ either PMB or laser stripping safely, dedicated facilities must be utilized that accommodates the particular removal method.

Investigative Question #4 Analysis

The fourth investigative question was to determine what will be future paint stripping environment regulations. The measurement questions related to the investigative question #4 are questions 29 through 33 in Table 6 and Appendix D. During the Delphi the experts reached consensus on question #32, agreeing that application equipment technology and dedicated facility design, regardless of method, will become

Table 6: Investigative Question #4 Measurement Questions

Investigative Question #4 Measurement Questions

#29) Chemical stripping will become banned from use because of environmental regulations in how many years?

#30) Plastic media disposal regulations will restrict its use for exterior airframe surface paint removal in how many years?

#31) Laser stripping will evolve as the predominant exterior airframe surface paint removal method because of strict waste disposal regulations that ban or economically effect other methods.

#32) Application equipment technology and dedicated facility design, regardless of method, will become increasingly important in light of future handling, disposal, and air quality regulations.

#33) New paint removal methods (other than chemical, plastic media blast and/or laser stripping) will evolve and become the predominant method because of handling, disposal, and air quality regulations.

increasingly important in light of future handling, disposal, and air quality regulations. The panel was unable to achieve consensus on any of the other measurement questions regarding investigative question #4.

This investigative question brought the widest range of responses in the measurement questions. Future regulation impact on each of the discussed methods was difficult to distinguish. However, the experts predicted that chemical stripping will become banned from use in 3 years, as shown in question #29 of Figure 13. Future environmental regulations concerning PMB waste disposal conveyed mixed

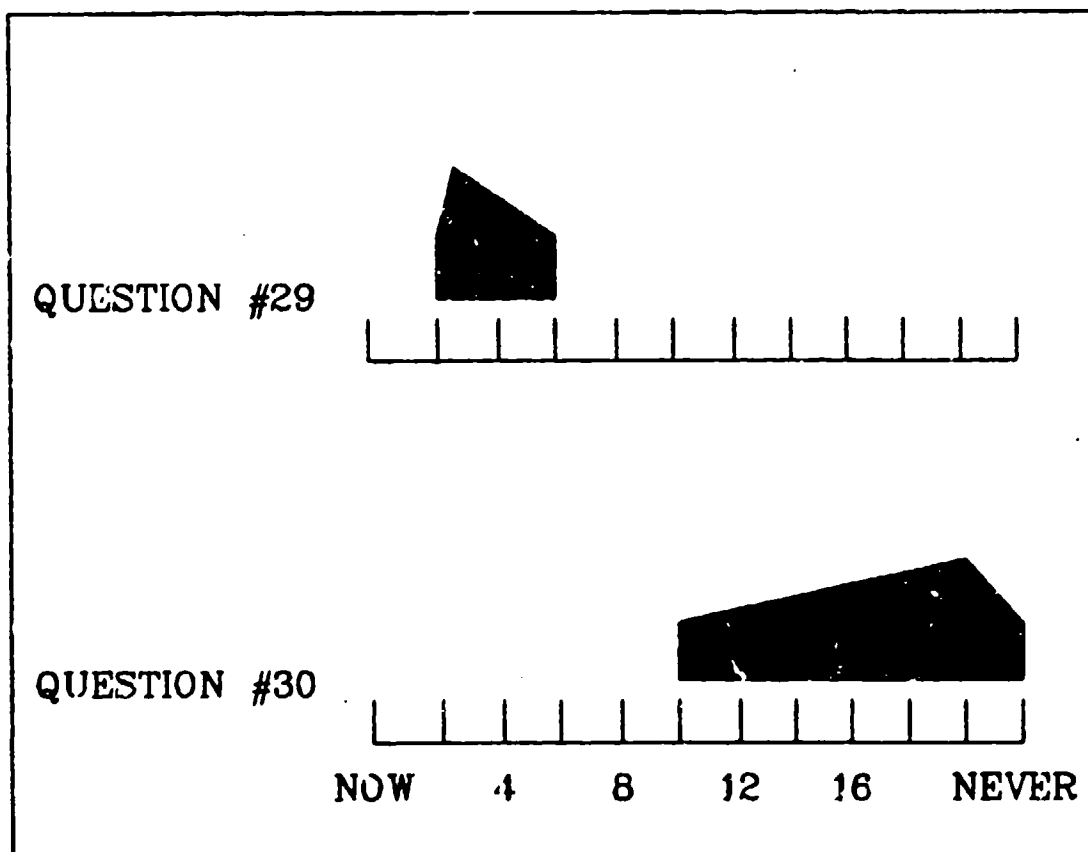


Figure 13: Investigative Question #4 Inter-Quartile Ranges

reaction among the experts. As a result, the panel responded PMB will be affected by future regulation in 20 years, but the inter-quartile range spans from 10 years to never. The results to the query are represented by question #30 in Figure 13.

The literature review revealed studies that optimistically found minute amounts of hazardous waste produced during laser stripping operations. Despite this information, the panel responded neutrally to laser stripping evolving as the predominant because of strict

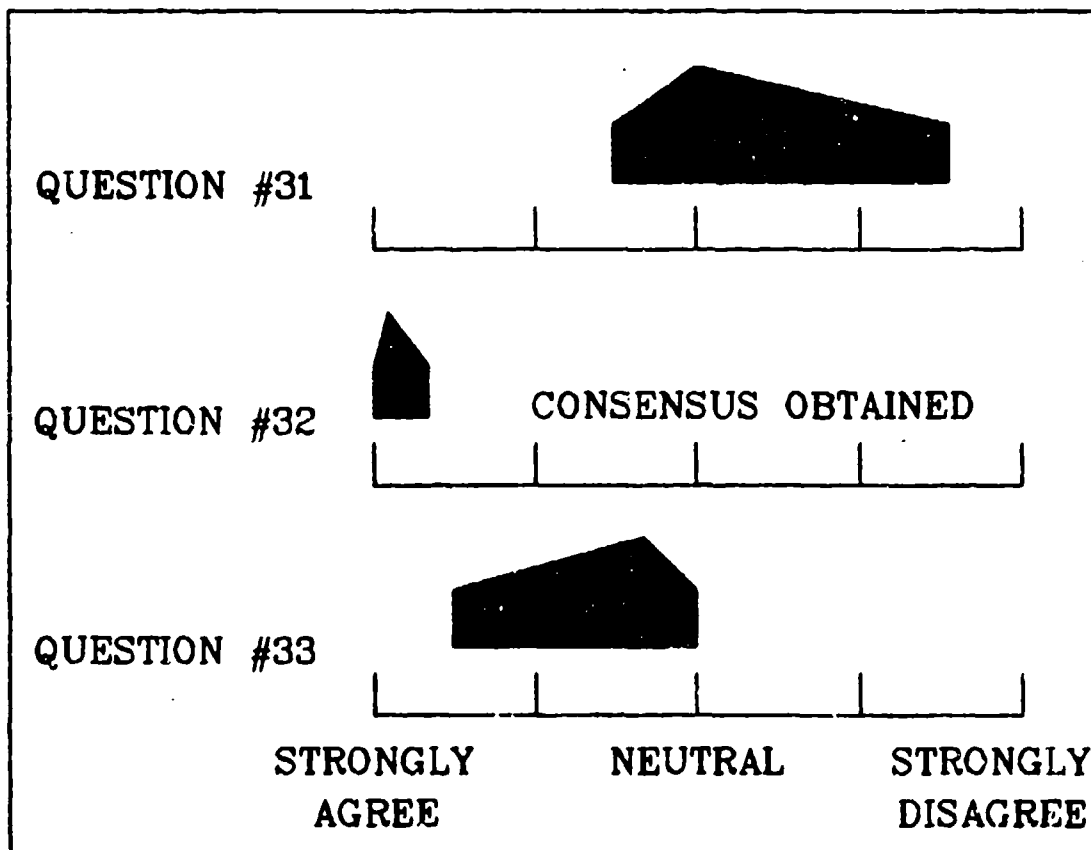


Figure 14: Investigative Question #4 Inter-Quartile Ranges

waste disposal regulations. The results are depicted by question #31, as shown in Figure 14.

The experts strongly agreed that application equipment technology and dedicated facility design, regardless of method, will become increasingly important in light of future handling, disposal, and air quality regulations. This consensus is shown by question #32 of Figure 14.

The last measurement question made the statement that new paint removal methods, other than chemical, PMB, or laser stripping, will evolve and become the predominant removal method. As depicted by question #33 in Figure 14, the panel displayed a neutral forecast, with the inter-quartile range spanning from agree to neutral. The experts further commented a new method is possible, but the method has yet to technically evolve for serious consideration. Comments made regarding this statement referenced new technologies in the paint itself, with paint development focusing on ease of removal or elimination of removal.

Findings For Investigative Question #4

The use of dedicated facilities was once again established as a must, but this time it was strongly agreed upon not because of worker safety but to observe environmental regulations impacting handling, disposal, and air quality. Because of future regulations, it was projected by the panel that chemical stripping will be banned from use in 3 years. It was unclear to the panel if

PMB will ever be affected by future environmental regulations, and undetermined if laser stripping's lack of harmful by-products will promote its use due to future regulations.

Although the panel did not disagree that another method, other than chemical, PMB, or laser stripping, will evolve because of environmental regulations, the panel failed to agree on the method. Some comments indicated the method would evolve through the paint itself, with the paint formulated for ease of removal or not removed at all.

In general, paint removal facilities must be designed to effectively handle and dispose of waste, while maintaining air quality standards. The banning of chemical stripping is eminent; predicted to happen in 3 years. Another form of paint removal, other than chemical, PMB, or laser stripping, will be developed due to strict environmental regulations.

Investigative Question #5 Analysis

The fifth investigative question was to determine how will future paint stripping methods be applied. The measurement questions related to investigative question #5 are questions 34 through 39 in Table 7 and Appendix D. During the Delphi the experts obtained consensus on question #38, agreeing the technology needed to reduce the explosiveness of PMB dust to a safe level is available now. Furthermore, the panelist agreed that PMB equipment that

restores air quality to an environmentally safe level is available now. The panel was unable to achieve consensus on any of the other measurement questions regarding investigative question #5.

The experts were unable to conclusively predict if robotics will replace human labor for paint removal in the next 15 or more years, demonstrated by the median response range shown by question #34 of Figure 15. The experts further agreed that a robot's reliability and ease of maintenance are primary concerns when establishing removing

Table 7: Investigative Question #5 Measurement Questions

Investigative Question #5 Measurement Questions

- #34) Robotics will not replace physical paint removal labor.
 - #35) In how many years will robotics become adaptable (programmable) to generate the precise movements needed to strip complex exterior airframe shapes.
 - #36) A robot's mechanical reliability and ease of maintenance are primary concerns governing robotic adaptability in a aircraft paint removal environment.
 - #37) Plastic media blasting equipment that restores air quality to an environmentally safe level will be developed in how many years?
 - #38) Plastic media blasting dust is explosive. The technology that will reduce the explosiveness to a safe level will be available in how many years?
 - #39) Plastic media recycling equipment that effectively separates heavy particles will become available in how many years?
-

methods utilizing robotics, as depicted by question #36 in Figure 15.

The panelists forecasted that in 6 years robotics will be programmable to generate the precise movements needed to strip complex exterior airframe shapes. This prediction is shown by question #35 of Figure 16.

Concerning PMB application equipment, the panelist agreed that PMB equipment that restores air quality to an environmentally safe level is also available now, as represented by question #37 in Figure 16. Furthermore, the experts obtained consensus on question #38, agreeing the

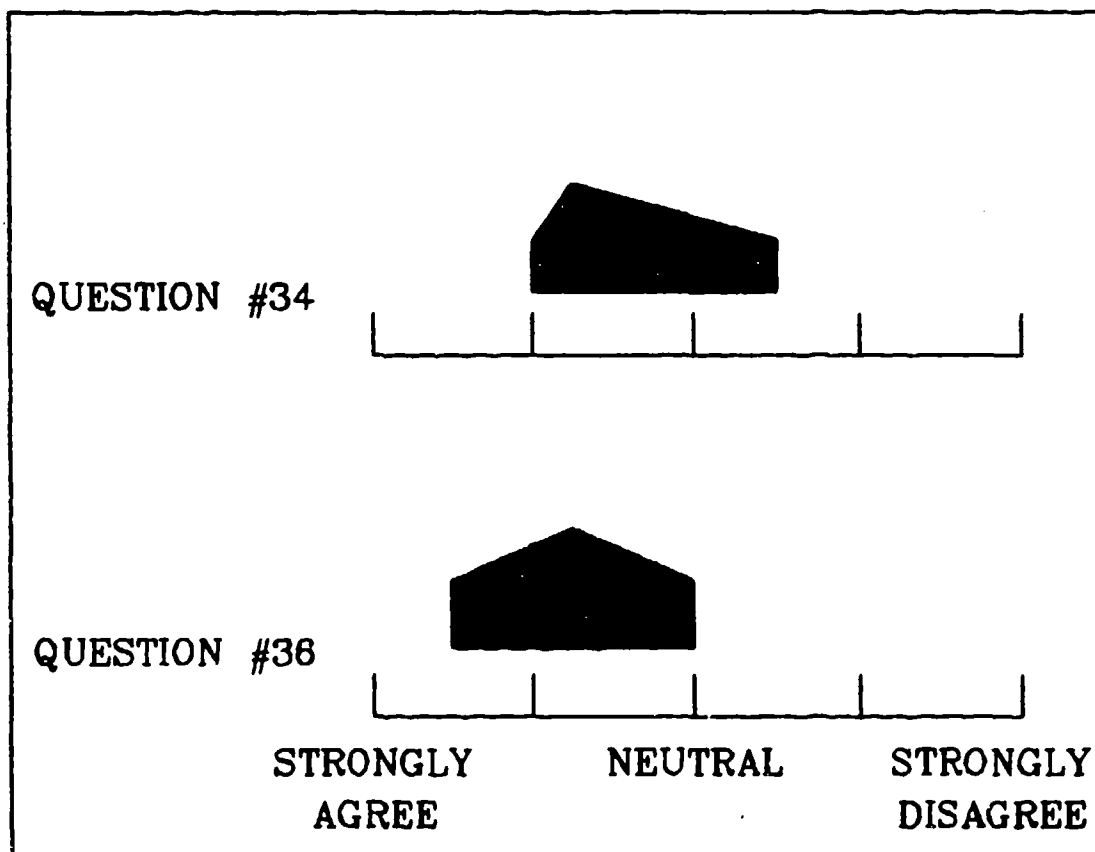


Figure 15: Investigative Question #5 Inter-Quartile Ranges

technology needed to reduce the explosiveness of PMB dust to a safe level is available now, as displayed in Figure 16. The experts determined that plastic media recycling equipment that effectively separates heavy particles will be available in 1 year, as shown by question #39 in Figure 16.

Findings For Investigative Question #5

Although the experts were not conclusive on many issues regarding robotics, they did conclude that programmable robotics that can handle complex aircraft shapes will be available in 6 years. The panelists did agree on two

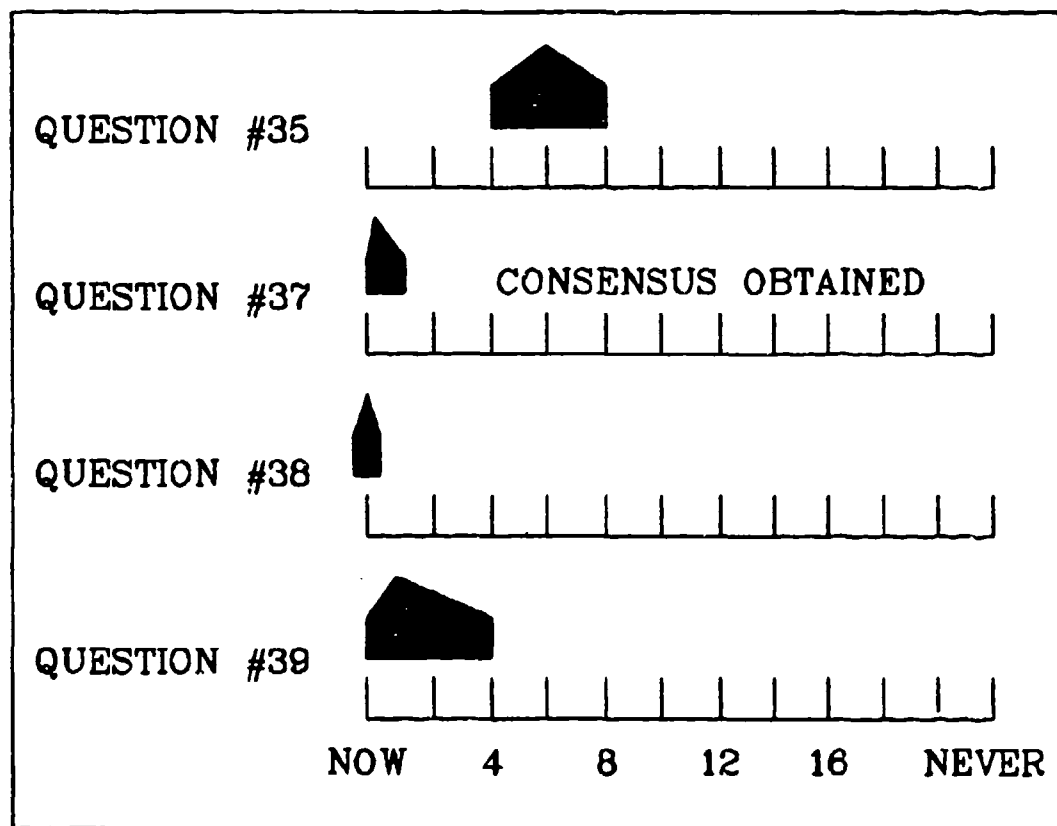


Figure 16: Investigative Question #5 Inter-Quartile Ranges

issues: PMB equipment that eliminates explosive dust and restores air quality to an environmentally safe level are available now, while the PMB equipment that can separate heavy particles will be available in 1 year.

Chapter Summary

This chapter analyzed the data obtained through the Delphi iterations. First, the data collection process was reconstructed, highlighting the time frames and expert participation during each round. Next, the overall Delphi results were discussed. Finally, each of the investigative questions were analyzed through related measurement questions. The measurement questions were analyzed using the procedures outlined in Chapter III, with the results provided in Appendixes E and F. The findings concluded for each investigative question were then presented, further defining the relationship between each measurement question and the respective investigative question. Next, Chapter V presents conclusions and recommendations based upon the information presented in Chapter IV.

Chapter V. Conclusions and Recommendations

Chapter Overview

This chapter proposes conclusions and recommendations founded upon the results obtained from the Delphi process. The chapter begins by addressing the original investigative questions; as a result, five conclusions are extracted from the research process. After the conclusions, five recommendations that suggest future aircraft paint removal logistical strategies are introduced. Finally, three additional research recommendations are presented that would enhance the knowledge obtained in this research.

Conclusions

Conclusion #1. As suggested by the literature review and determined through the Delphi, chemical stripping will be replaced in 4 years by plastic media blasting as the predominant exterior airframe paint removal method. Chemical stripping will continue to be used for some small components, specifically those 18 inches in diameter or less, or component's whose shape or substrate composition requires chemical stripping. Plastic media blasting will continue to be used indefinitely for complete exterior airframe paint removal. Another possible method that would be used for large components such as rudders, wings, and exterior airframe surfaces, is laser stripping. It is unlikely that plastic media blasting will be replaced by

laser stripping due to the method's high costs and/or unresolvable technical difficulties. If laser stripping hurdles the economic/technical barriers, it is undetermined when the process will replace plastic media blasting as the predominant exterior airframe paint removal method. Furthermore, it is unlikely that any other known paint removal method will become the predominant paint removal method in the next 15 years or more. Therefore, the projected paint removal method that will suit future paint removal needs is PMB, and no other method is projected to be a serious threat to PMB's dominance.

Conclusion #2. The method underlying plastic media blasting requires no further research and development; however, process enhancement can be obtained through further researching the process's procedures and parameters. Exemplifying this statement, current plastic media blasting configurations can safely strip composite substrates, but only under controlled conditions and skilled operators. Research that will develop laser stripping into a competitive paint removal method will take 10 years, but laser stripping research and development must be united with robotic development for the method to become successful. Robotic usage can also be adopted for other removal methods, with the development taking place in 4 years. Therefore, PMB's process and parameters must be further researched to optimize the method's effectiveness. Laser stripping must continue to be researched; however, immediate returns on the

research investment are unlikely. Robotic development for both laser stripping and other removal methods requires research, especially if laser stripping is to be seriously considered.

Conclusion #3. Equipment that environmentally protects the worker while performing chemical stripping is available now. Because of the availability of protective equipment, it is questionable if the worker should be removed from the chemical environment. For plastic media blasting, the equipment that environmentally protects the worker is available today. Other than protective equipment, the environment can be further controlled with dedicated facilities that are designed, or retro-fitted, for either plastic media blasting or laser stripping. Therefore, the worker's safety can be further enhanced by both protective equipment that is available today, and facility construction that is specifically designed for the given removal method.

Conclusion #4. Regardless of the paint removal method, future regulations will dictate the necessity of dedicated facilities that control handling, disposal, and air quality issues. Because of the hazardous chemicals associated with chemical stripping, banning appears emanate in 3 years. Additionally, it is unclear if plastic media blasting will ever be fatally affected by future environmental regulations. Furthermore, it is undeterminable if the low/zero by-products produced with laser stripping will dictate this method's use because of strict waste disposal

regulations. An alternative to chemical, plastic media blasting, or laser stripping might evolve because of possible strict regulations; however, the method is undeterminable. Therefore, facility design is the major consideration when defining a paint removal's environmental effects. Chemical stripping facilities should be converted to an environmentally safe method, namely PME.

Conclusion #5. Although it is debatable if robotics should replace human labor, programmable robotics that can conform to complex aircraft shapes will be available in 6 years. Other application related issues involve plastic media blasting and the process equipment. Equipment that eliminates explosive dust and restores air quality to an environmentally safe level is available today. Additionally, plastic media blasting equipment that can separate heavy particles will be available in 1 year. Therefore, it is undeterminable if robotics will replace human labor. One possible reason is that robotic paint removal, regardless of method, is not presently perfected. Equipment that safely applies PMB is available today, while the equipment that further the method's effectiveness of separating heavy particles will be accessible in 1 year.

Recommendations

Recommendation #1. Since the plastic media blasting method is fully developed and will replace chemical stripping for an indeterminate time frame, depots should

fund for the process's full implementation. The funding should emphasize three important aspects: worker training, safety equipment, and dedicated facilities. Worker training will assure the process is controlled and applied properly, avoiding potential damage to high cost substrates. Safety equipment that protects the worker while allowing him/her to perform their duties is also a significant factor if the process is to be accepted by the worker. Last, dedicated facilities that enhance the plastic media blasting process with efficient media recovery and environmental control will further add to the stripping quality while strategically saving money.

Recommendation #2. Dedicated facilities are required to protect the worker while handling, transporting, storing by-products, and maintaining air quality standards. Full evaluation for possible retro-fitting of existing buildings should be performed before appraising construction of new buildings. The facilities should be large and adaptable for plastic media blasting and robotic usage. Electrical wiring should also be convertible for robotic requirements.

Recommendation #3. Research for laser stripping should continue; however, at a slow pace for two reasons. First, laser stripping involves using robotics, an economic situation the Air Force can not presently afford. Second, solving laser stripping technical problems will not happen overnight; therefore, it is fruitless to fund an all out effort that will not immediately benefit the Air Force

today. The money that would have been used on laser stripping development will be better utilized developing plastic media blasting's process and parameters.

Recommendation #4. Economic evaluation should be conducted for using robotics with plastic media blasting and laser stripping. If economically justifiable, robotic development should be funded so that the technology is developed when the Air Force can budget robotic labor.

Recommendation #5. Paints that are composed of non-traditional elements should be fully researched. Paints that are not limited to enamel and polyurethane composition may lend themselves to simple, economic, and environmentally safe removal methods.

Further Research Recommendations

Research Recommendation #1. As determined in the study, dedicated facilities are a necessity regardless of removal method. Further study revealing the best universal design that can be adapted to a variety of possible removal methods would avoid complete facility design when new methods are implemented.

Research Recommendation #2. An important consideration to determine if robotics should be instituted is economic and socialistic rewards. An analysis of a robotic program for plastic media blasting and laser stripping could determine specific break-even points that a robotic program must hurdle to become justified. Furthermore, social

considerations that a robotic work force offers should be qualitatively investigated.

Research Recommendation #3. Future paint removal methods may not be established on removing enamel and polyurethane paint. As the study determined, the paint itself may be constructed for the ease of removal and/or no removal. Therefore, further study investigating different chemical paint compositions should be evaluated.

Chapter Summary

This chapter presented conclusions and recommendations founded upon the results obtained from the Delphi process. The chapter began by addressing the original problem statement, integrating five conclusions extracted from the research process. After the conclusions, five recommendations that suggested future aircraft paint removal logistical strategies were introduced. Finally, three additional research recommendations were presented that would enhance the knowledge obtained in this research.

Appendix A: Initial Request Letter

AFIT/LSG
ATTN: Capt Then
WPAFB, OH 45433

November 14, 1988

Dear _____,

Let me introduce myself. I am Capt Michael Then, an aircraft maintenance officer who is currently a logistic management student at the Air Force Institute of Technology (AFIT).

Due to environmental hazards and budget constraints, future aircraft paint removal methods are major concerns to both the Air Force and the aircraft industry. For a thesis, I am investigating the future of aircraft paint removal and applications. The research will include a Delphi method of gathering expert opinions to forecast the future in a given subject area. The Delphi method is an iterative series of questionnaires (usually 3) that, in this case, ask opinionated questions about paint removal methods, application techniques, and the future of these subject areas. The questionnaire contains approximately 50 questions that can be answered on a scale rating, ranging from 1 (fully agree) to 10 (strongly disagree). Each question also has the option of expressing the answer in writing.

I am seeking corrosion control experts interested in participating in this Delphi research via mail. Your participation is highly valued and would significantly contribute to this project's success. Please indicate if you want to take part in this research on the enclosed pre-addressed postcard. If you have any questions circle "questions" on the postcard and I will call you. The first questionnaire will be mailed in December and the final results will be made available for you. Looking forward to hearing from you!

Sincerely,

[Signed]

Michael J. Then, Capt, USAF
AFIT Logistic Management Student

Appendix B: First Iteration Responses

1. What paint removal methods are likely to suit future needs?

- Laser stripping and plastic media blasting.

-Plastic Media Blasting (PMB) - This will most probably be an interim method of choice among the depot maintenance facilities. PMB will also probably replace chemical stripping done at field level as smaller, more flexible PMB machines become available and affordable. At the depot level, however, PMB will only be implemented for as long as it takes to develop and outfit each depot with the "next generation" of paint removal methods. PMB will also probably be used for special applications or for small parts stripping at the depots.

Lasers - This is the next generation of paint removal methods. It will most probably replace PMB for stripping large areas such as entire aircraft or large parts. This replacement will take place in the depots in about five years (at the absolute soonest).

Chemicals - We'll never get away from chemical stripping. It will remain to be the method of choice for use on special parts such as radomes and on complicated parts where the versatility and coverage of a liquid stripper is needed.

- For major and minor paint stripping tasks:

 - Plastic Media Blasting.

 - Sodium Bicarbonate Blasting.

 - Laser.

 - Chemical.

- For specialized areas:

 - High pressure water blast.

- I believe Plastic Media Blast (PMB) will serve our present and future needs. Automation of PMB will be a plus for future needs on stripping paint from delicate composite substrate and other advanced materials. Laser paint removal may also prove to serve our future needs. There is still allot of unknowns with this technology.

- For thick-skinned aluminum aircraft, PMB will probably suit future needs provided media ingress problems are solved.

For thin-skinned aluminum aircraft, no preferred alternative to chemical removal is immediately obvious. Further developmental work may indicate controlled PMB

possibilities. Laser removal techniques will also require additional study.

On composites, it is my understanding that there is not an approved chemical method for stripping paint. By default, the PMB method would appear to be the best method currently available.

- Laser is in development now and may be in production in five years.

- Chemicals are very likely to be phased out as hazardous. Beads will fill needs in the interim, then lasers will become the major method; especially with paint on metals.

- Chemical stripping will be used far into the future. It will obviously require improved techniques for control of the used stripper related to pollution control. Plastic bead blasting at this time is the only acceptable alternative. Sanding will continue to be used in the operational command level.

- Plastic media blasting in most applications of exotic materials, thin skinned aluminum, encapsulated electronics, rubberized coated structures, malleable and ductile materials. This is and will be the stripping technology of the future:

 - Robotic plastic media wheel stripping equipment.

 - Laser for some specific applications of non-reflective flat surfaces with robotic applications.

 - Flash lamp for quick removal of thick layers of paint from large applications (steel hulls of ships).

- PMB now appears to have the potential for handling all future metallic and non-metallic substrate paint stripping requirements. However, considerable R&D will be required to optimize media type, air pressure, standoff, angle, etc., for each application.

- Plastic Media Blast.

- It is my opinion that plastic media blasting will suit the needs for the foreseeable future. This process will be refined, monitored, and fine tuned up to and including robotics.

Some where in the future the laser will come into the picture, but it is in my opinion, that this process will be too expensive for anyone except the government to consider.

- Plastic Media Blasting; water jets; thermal; scrapers; laser; paint elimination - self protecting materials including variable color materials or stains; permanent paints; lifetime paint protective coatings;

permanent protection; sandwich materials; "command destruct" coatings; coatings that peel on cue; "system" coatings; coating that have built in removal techniques.

- Plastic Media Blast.

- Dry stripping in the near future. Perhaps laser stripping in the future.

- The materials of the future will be composites and ceramics; therefore, paint removal methods must be non-damaging to these materials. Environmental concerns will also be a strong driver. Economics has been an issue. For these reasons, the two leading candidates are laser and biological stripping.

- Plastic grit blasting; sand blasting - glass bead blasting; walnut shell blasting (organic shell blasting); chemical paint stripping; sanding/scraping/chipping; thermal paint stripping.

2. What research and development efforts will the new methods require?

- Process development as well as hazardous waste clean-up.

- Plastic Media Blasting(PMB) - PMB's effects on metal have been fairly well categorized and the method has been modified and tailored to allow it to work on metal surfaces without damaging the substrate. PMB's effects on composites, however, are just beginning to be understood. The main area for further research with this method is that which examines the effects of PMB stripping on various configurations of composites(thin skins, honeycomb cores, thermoplastics, etc.) as well as on new types of surfaces (those with lightning protection built in, "smart" skins, RAM/RAS, etc.)

- Lasers - Lasers need to be examined and researched starting from scratch. The type of laser, type of beam, beam delivery system, robotic controller, vision system, power supply, safety systems, air collection and filtration system, and facility design all need to be designed, tested, and optimized. Currently, work is being done to examine the effects of pulsed CO2 laser on some materials, but other lasers are also candidates for use and must also be examined. In order to make laser paint stripping a reality, a concerted effort is needed on the part of AFLC us in AFWAL, the ALCs and experience being gained by the Navy in its procurement of a laser stripping system.

- Chemicals - Research is needed to develop less or non-toxic chemicals which can be used for the small number of applications for which they will be used in the depots. This

research must be conducted with EPA and OSHA considerations in mind and must also determine the effects which these new strippers may have on stripped substrate.

- Chemical: find safer, less hazardous compounds.

PMB: completed.

Sodium Bicarbonate Blasting: Fatigue life, fatigue crack growth rates, corrosion potential to include entrapment of sodium bicarbonate and water in seams and flying surfaces (reverts to NaOH and CO₂ at higher temperatures), cost of the method (economics).

Laser: AI systems, robotics, software, and sensor technologies all direction and control of the stripper beam. I believe material studies (effects to aircraft structure) are complete.

High pressure water blasting: none.

- PMB is state of the art now. The only remaining development would be heavy particle separation from reusable plastic media. However this is currently on the edge of reality. It will soon be proven and available.

Laser paint stripping needs a great deal of research and development. Areas needing research are: material characterization (damage to substrate being stripped), environmental controls, waste controls (environmental concerns both air quality and solid waste handling), safety, noise, beam delivery, type of industrial laser needed. These are some of the questions that need to be documented and included in a design for a new stripping technology with lasers.

- Assuming that PMB is the only practical alternative to chemical stripping, as the EPA restricts the use of chemicals, it will be very important to:

Develop better media, if possible (optimum hardness, specific gravity, angularity, resilience, price, slower media break up rate, and repeated collisions).

Develop charts or equations which will relate particle energy with particle count, media mass flow rate, flowing air pressure, etc.

Right process pressure specifications based on the above.

Improve media reclamation. This system needs to be as good as it can possibly be because it has a big impact on the quality and the economics of the process.

- Robotics will be necessary for laser or any future method.

- Laser paint stripping is still at a very early stage so it will need much development not only to better understand the process but to design the machinery of paint strippers as well. The control of the stripping products

from the laser process will also need to be brought to the point of meeting present and future EPA standards.

- Improved techniques for masking aircraft during plastic bead blasting to prevent intrusion of beads into the aircraft interior. Improved methods of disposing used beads.

- Plastic media blasting is still in the 1800s sand blast technology in the U.S.. If the U.S. is to catch up with the European PMB stripping technology, we must either adopt their superior equipment or develop our own. This will require the development of:

- Media flow rate controls, accurate to pre-selected quantities (pounds per minute of delivered media) by at least 98%.

- Media cleaning apparatus that will remove all dust paint chips and all small media particles to 99.8%.

- Dense particle separator that removes all hard particles to 99.85%, regardless of number of recycles of the media or amount of trash in the media.

- Media size grading and replenishment apparatus. You must have a method to pre-select the size of media you want to strip with or the combination of sizes and percent. We must be able to pre-select sizes and % of mixes and keep this loaded and being recycled. Smaller media sizes we desire to keep (for other applications) can be removed and stored as can sizes larger than we desire to recycle. As media is broken down and removed (either to the trash container or to future use storage bins), media must be automatically replaced, allowing media particle size to be an unknown is a major problem and can cause substrate damage.

- A strip analysis with micro photography, energy saturation curves, and arc height measurements must be made for all substrate to be stripped to determine median flow rates, media sizes, pressures and proper impregment angle. For composites, we must be concerned with resin removal, fiber and matrix rupture.

- For robotics, the best application appears to be a centrifugal wheel dispensing media. Wheel speed is computer controlled via an amp sensitive electro-hydraulic vane impeller. Media delivery is by an amp sensitive motor driving a screen auger. All portions of the machine are computer controlled for each specific aircraft or missile substrate.

- Considerable R&D will be required to optimize media type, air pressure, standoff, angle, etc. for each application.

- Robotics should be investigated to eliminate non uniformity resulting from individual operators techniques. There should be a clearing house (inter-service) to document and categorize data from all sources and to issue standard procedures for all types of paint removal requirements.

- Refine blast parameters (PMB) for composites. Such as work being done at AFWAL/ML.

- I think that the equipment manufacturers are going to need some sort of joint venture money to develop what the aerospace industry is going to require.

At the present time there is so much false data being thrown around, unless you are involved on a daily basis, you do not know what to believe.

- Plastic Media Blasting - damage assessment and parameter optimization.

Water jets - technology adaption and adjustment, damage assessment, parameter optimization.

Thermal - damage assessment, parameter optimization, economic assessment.

Scrapers - development, damage assessment, economical evolution, overcome initial un acceptability.

Laser - damage assessment, parameter optimization, control and feedback, automation, economic assessment.

Paint elimination - new materials development (lots of \$\$!!).

Permanent paints - materials development and acceptance tests.

Permanent protection - materials development and testing.

Command destruct coatings - materials and methods development, communication between designers-operators-maintainers and repairers.

System coatings - materials and methods development, communication between designers-operators-maintainers and repairers.

- Paint removal from composites.

- Effects of PMB and lasers on a variety of substrate in systems today as well as tomorrow, such as exotic composites.

- New compounds (PMB); definitive analysis of amount/types of contaminant which can be tolerated; standardized requirements for integrated facility/process/operator (MUST DO!).

- Development of: better quality media, aircraft quality delivery systems, high density contamination separation devices.

- To my knowledge, biological stripping is only a concept with high potential payoff. Basic research to achieve demonstrated feasibility are required, followed by applied research, development, and prototype evaluation.

The feasibility of laser stripping has been demonstrated, but many issues must be addressed in a development program such as:

- most efficient wave length.
- how to cope with non uniform composite surfaces.
- best feedback control system.
- verify base materials are not damaged.
- develop safety systems.

- develop larger lasers for more rapid processing.
- evaluation of waste and waste disposal requirements.

- USBI Corp. is presently developing a florescent plastic media to aid in detection of residual grit/surface smears/crack masking etc., under an R&D program managed by myself. We are producing a commercial lot of type II material in compliance with MIL-P-85891, which will be tested this year.

3. What worker safety considerations will impact paint removal methods?

- For PMB and future chemical stripping, exposure to the stripping medium will be the most important safety consideration. Exposure must be limited as much as possible or it must be made less hazardous. This can be accomplished through the use of robotics and less toxic chemicals.

Lasers pose many new problems which must be overcome. Most of these problems concern the laser beam itself. Workers must be protected from the beam lest it contact their skin for long periods of time, or their eyes for relatively short periods of time. These problems can be taken care of with the use of robotics and a protective enclosure around the aircraft.

With robotics, another safety consideration is that the robotics, themselves, do not pose a threat to the human operators through their fast movements and rapidly changing work envelopes. Care must be taken to avoid robot/worker collisions.

- Plastic Media Blasting: potential carcinogen of paint dust, dust explosivity/flammability.

Laser: beam dangers, potential carcinogen of vaporized coatings.

High pressure water blast: danger of cutting stream.

Sodium Bicarbonate Blast: potential carcinogen of paint dust.

Chemical: carcinogen and skin irritant.

- It would be advantageous to remove the worker from the stripping environment (i.e. automation). If it is (?)

all normal safety consideration will apply (i.e. noise, dust, vapors, chemical burns, etc.).

- If the PMB method is adopted the following safety items need to be addressed:

- One way airflow over waterfalls and supplied air to operators.

- Take steps to control fire hazard from PMB dust in the airflow and also in the dust collection system itself.

- Proper collection and disposal of paint and primer removed by the PMB method (good reclamation and segregation system).

- EPA will shut down all chemical stripping soon. PMB is probably the safest for personnel, but reduces fatigue life. Laser can only be done by robotics safely.

- Chemicals have very direct impact on worker safety and any findings such as the carcinogenic nature of some major stripping methods can profoundly affect what processes are allowed. Alternative methods also can have safety issues such as the generation of heavy metal particles in the air by beads or gases by laser methods. The danger of stray laser beams or robotic equipment is also an issue with laser paint stripping.

- Plastic media: most all safety considerations are in place and understood. I recommend all breathing helmets not have a hose to them for this poses a tripping hazard. I feel a ni-cad battery pack will deliver hospital grade clean air for 4 hours, then swap out the rechargeable battery.

- Laser: eye protection is a must. This operation will most definitely require electro mechanical robotic controls.

- Flash lamp: eye protection is a must for this human operated machine. Lamp curtains must seal tightly against substrate to prevent light leakage.

- Proper breathing gear, gloves and clothing; hazardous waste handling and disposal; handling methods of PMB nozzles; acceptable lighting levels.

- Chemical strip - carcinogenic fumes. PMB - no worker safety problems when using proper equipment.

- The worker has to get away from the dangers imposed by chemical stripping. The fumes from wet stripping cause some offices at major airlines to be evacuated.

- Paint coating toxicity, removal materials hazards and toxicity, waste collection techniques, waste isolation, noise, vision impairment, physical requirements (work conditions, need for special clothing, work area), equipment hazard potential, safety training and precautions requirements.

- Noise, dust.
- Chemistry of the coatings and working conditions.
- Already covered well by OSHA, EPA, etc.
- Chemical solvent related injuries and health problems.

- Lasers powerful enough to remove paint will be damaging to humans. Safety systems must be developed to assure human exposure will not occur.

Biological - unknown.

PMB, sandblast, and water jet have similar safety considerations; although not necessarily to the same degree. The primary concern is the impact of the abrasive material.

- Chemical paint stripping is hazardous and environmentally polluting; USBI is minimizing its use.

4. What will be paint stripping environmental regulations impacts?

- EPA/OSHA laws will continue to guide paint removal methods. Waste products will remain, most likely, to be the limiting factor, and regulations restricting waste products will, no doubt, become stricter in the future. Lasers have an advantage here because the amount of waste which they produce is so much less than that produced by PMB or chemical stripping. However, lasers are also a tool for which many safety regulations already exist concerning their use in other applications. Laser usage will be most limited by these usage regulations.

- Reduction or elimination of chemical stripping.
Regulation of all waste from any stripping method.

- Environmental regulations will include hazardous waste, controlling air and water quality. Regulations have basically eliminated a wet chemical process. The air quality regulations will also require all air emissions to be controlled, contained, and properly cleaned prior to release.

- Proper collection and disposal of paint and primer removed by PMB process (good media reclamation system and air handling system is crucial to accomplishing this).

- EPA will be more strict on DOD facilities and will eliminate chemical stripping completely. PMB can be used in the interim until the laser technology is perfected.

- Regulation impacts paint strippers and visa versa. A change in the allowance of certain chemicals, for example, could dramatically change the kinds of stripping processes in general use. By the same token, new regulations will be formulated to cover the issues of importance in the new processes. Each new process will doubtlessly have certain specified areas which by nature requires regulation (eg. powders with beads, gases with lasers).

- The use of chromates in anodizing, conversion coatings, and primers are being considered for banning. These chromates are involved with all stripping operations as related to pollution control.

- Chemical stripping is on the way out for good due to the hazardous waste disposal problems, the release of high volatile organic compounds, worker hazards, and shortage of water.

As EPA tightens the controls on the dumping of plastic into landfills, we must insure we have high tech cleaning equipment that will allow us to use our media longer and reduce the cost of landfill disposal. Waste plastic media with paint chips, sealants, etc., will all require testing to determine the levels of : arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. We must develop small efficient blast furnaces to burn the media thus reducing the volume by 95%. The USAF alone produces about 4 million pounds of dirty media a year. The majority is thrown away because it is so full of paint chips and dust that it will no longer "cut". This is due to poor cleaning ability of the machinery installed. The USAF pays \$0.13 per pound for disposal or \$520,000. Then another 4 million pounds must be purchased at \$1.80 per pound or \$7,200,000. A good cleaning and dense particle remover would save at least 60% of the disposal and purchase or \$4,632,000 per year..strictly by removing trash so the media would continue to "cut" the paint off the substrate.

- Severe constraints are being imposed on use and disposal methods of existing chemical stripping compounds. It will be necessary to develop improved methods of disposal, recycle, alternate compounds to meet future EPA constraints. If a dramatic improvement is not achieved, chemical stripping will most probably be banned.

- Environmental regulations will restrict chemical stripping; determine handling of wastes from all forms of stripping.

- I fully expect EPA to ban wet stripping in the near future.

- Restrict locations for stripping, dictate safety equipment, limit releases (dictating waste collection methods), cause preference of immediate containment and collection of waste, give economical advantage to non-dusty (wet?) methods, give advantage to methods that separate and treat the hazardous waste on location.

- Primer and paint that can be disposed of in local landfills and not require hazardous material handling.

- Research into the coatings, OSHA rules and EPA (i.e. disposal).

- Very controllable with a PMB operation.

- Probable significant economic impact to utilize chemicals if pending regulations are adopted and enforced.

- Costs of handling and disposing waste will push paint stripping to the technologies that yield the smallest quantities of hazardous waste and/or the easiest handled waste. Disposal costs are generally based on the quantity of material with little regard for the contamination level.

- Again, contamination of ground aquifers, and storage and disposal of waste are problems.

5. What will comprise paint stripping application equipment?

- It depends on your process. Laser stripping, for example, will require a (yag) laser. Plastic media blasting will require a blasting booth. Chemical stripping - no (operational) equipment.

- Paint stripping equipment will continue to become more high tech. Robotics - These are being developed for use with PMB methods and will most probably be a necessity for use with the PMB methods and will most probably be a necessity for use with lasers in order to get the human operator out of the stripping envelope which could be a dangerous/hazardous place to be when laser stripping is taking place.

Vision Systems - A must with robotics in order to allow the method (PMB or lasers) to be used in such a manner as to eliminate as much of the operator interaction as possible. Automated stripping systems will never be able to completely clean an aircraft (touch-up will always be required), but vision systems will allow automated systems to get the aircraft stripped down as much as possible.

Dedicated Facility - No longer will painting and stripping be able to be performed in the same building due to dust from PMB operations and due to safety considerations with lasers. This will mean that a separate stripping

facility will be required complete with power, airflow, and waste disposal requirements.

Waste Collection/Treatment - Any method used in the future will require some sort of system which will permit the safe collection, consolidation, and detoxication of stripping waste. This may be as simple as a series of filters to clean the air from laser paint removal operations which convert the stripped paint into largely non-hazardous vapors. However, it may be as complicated as a multi-stage media separation system to remove impurities from plastic media material.

- Depends on the method. There does seem to be a lot of interest in robotics right now.

- Any new method will need to be automated. We must design new equipment, methods to be automated removing the worker from the hazardous environment. Current manual equipment for PMB includes work stands to access aircraft, supplied breathing air hoods, blasting equipment outside the room, blast hose inside the room, media recovery and reclaim equipment outside the room, ventilation equipment including dust collectors to filter ventilation air.

- Plastic media blasting machine:
A good even-flow media feed system with positive control.
The proper ratio of hose to nozzle cross-sectional areas.
Converging/diverging nozzle.

- Air dryer on inlet to blast machine.
Portable, ease of handling.

- Media reclamation system: must be able to reclaim a high percentage of reusable media and discriminate against foreign particles (sand, paint, primer, sealant, ferrous and non-ferrous metals).

- Air handling equipment:
One way air flow toward cascading waterfalls.
Breathable air supplied to operators.

- Shop aids:
Scaffolding and/or rope and pulley system so that operators can access difficult to reach areas of the airplane. Good masking materials and methods to protect sensitive portions of airframe and to prevent media ingress.

- PMB equipment requires development work in heavy particle separation to avoid reducing fatigue life of thin aluminum. Monitoring of PMB flaws and pressures is very important.

- Paint stripping appears to be going towards automation. This means a trend from manual tools like brooms, brushes, and squeegees to larger equipment such as used with bead blasting to finally full scale, fully robotic systems being used with lasers (or beads). At this point it

does not seem likely that large scale paint stripping will stay with manual methodology for very many more years.

- If U.S. manufactures like Empire, Zero, etc.. have anything to do with it the equipment of the future will be simple single chamber pressure vents, no dense particle separator, no media graders, 1800s technology for air cyclone/air wash to remove dust and paint chips, gravity media feed, screen valve and pinch tube media flow rate control, etc.. All this equates to damage to aviation substrate. If we get smart and follow Schlick Corp, MBB, Aerospatiale and Luftonza of Germany and France we will have: stripping robots that can each out produce ten men with hose and nozzles. We will reduce our media consumption by up to 4000%, control media flow rates to 98% accurate, grade by media size to 95% accurate, clean media to a 99.9% factor, eliminate all hose surging, off set our skilled shortage of hose operators by 98%, increase production rates up to 2400% and control all functions with a teach-in computer system.

- Existing proven designs exist for PMB systems. Excellent results have been achieved where all operating parameters are strictly controlled.

Other removal methods, laser, CO2 pellet, etc. have not been demonstrated to be viable methods of paint removal, although research in these fields is continuing.

- PMB will comprise: blasting (media delivery) unit, recovery unit, reclaim unit (dust separator-cyclone, air wash, vibrating screens, dense particle separation), dust collector, vacuum producer, operator safety equipment, facility ventilation equipment, and possibly robotic control.

- Modern, state of the art delivery and recovery systems, proper ventilation, and dust collection systems, high production, high efficiency (95%+) particle separation systems.

The above coupled with high quality operator training for a high quality operator. The operator cannot be the bottom of the barrel worker. The job must be upgraded.

- A system that: separates paint from substrate; collects all residue; treats all materials; compacts waste material for disposal; treats materials for recycle; automated; detects completion of work; detects condition of substrate; detects surface condition; and does surface conditioning. Alternatively the system could do non destructive testing of substrate and/or coating (if there is a coating).

- I have P & G equipment.

- With dry stripping, industry must address the operator techniques, substrate, coatings, etc., and assume (with a high confidence level) that equipment will not damage substrate.

- Too extensive and application-specific to document here. Come see our setup at Boeing Helicopters.

- Sophisticated PMB systems, well controlled and monitored limited chemical applications.

- Within DOD and large commercial facilities, stripping operations will be highly automated. Operators will be located in a control room, separated from the operating equipment. Expert systems will control the stripping operation and simultaneously inspect the equipment for substrate defects.

Smaller commercial operations may require operator interface, but will be computer controlled.

- USBI is developing advanced computerized robots to accomplish automated coating removal using various media. A detection system is also being developed for contamination.

Appendix C: Demographic Questions

1. What is your highest educational level (if degreed, what major)?

- 1) B.S. (Chemical Engineering)
- 2) B.S. (Chemical Engineering); M.B.A.
- 3) B.S. (Mechanical Engineering); M.B.A. (Finance)
- 4) PhD. (Mechanical, Nuclear, Ceramics)
- 5) M.S.
- 6) M.B.A. (Industrial Management and Higher Education Administration); PhD. in Educational /Training almost complete
- 7) B.S. (Mechanical Engineering)
- 8) B.S. (Chemical Engineering); M.S. (Science Administration)
- 9) B.S. (Civil Engineering)
- 10) B.S. (Petroleum Engineering)
- 11) B.S. (Chemical Engineering)
- 12) PhD. (Electrical Engineering)
- 13) M.S. (Industrial Engineering); M.A. (HR)
- 14) B.S. (Mechanical Engineering; ASNT Level III (magnetic particle and penetrant inspection)
- 15) B.S. (Business Administration)
- 16) B.S. (Mechanical Engineering); M.S. (Engineering Mechanics)
- 17) B.S. (Mechanical Engineering); M.B.A. (Technical Administration)

2. What is your rank (military) or position (civilian) with your present employer?

- 1) GM-14
- 2) GS-11
- 3) President and C.E.O.
- 4) Manager, Group Leader
- 5) GM-13
- 6) Vice President and Owner of a PMB consulting firm
- 7) 1Lt, Project Engineer
- 8) GS-12
- 9) GS-11 Mechanical Engineer, Process Facilities Engineer
- 10) Manufacturing Development Engineer
- 11) GS-12 Industrial Engineer
- 12) Principal research scientist
- 13) Vice President & General Manager
- 14) Senior Research Engineer (Manufacturing Technology)
- 15) Vice President Sales and Marketing
- 16) DOD Program Manager
- 17) Senior Materials Engineer

3. If you served in the military (or presently serving), what is your military background and number of years served?

- 1) Army; 1943-1945
- 2) Army; 2 years
- 3) N/A
- 4) Air Force (not U.S.); Fighter pilot (5 years active, 4 years reserve)
- 5) Electronics technician 4 years
- 6) Air Force; 21 years Lt Col (Ret.) Aircraft Maintenance, Aerospace Engineering, Corrosion Control, and Logistics
- 7) Systems support division 2.5 years
- 8) N/A
- 9) N/A
- 10) Air Force; 1968-1972 rank E-4
- 11) Navy; 1952-1956
- 12) N/A
- 13) Air Force; 31 years 0-6 (Ret.) Pilot, Logistics, Operations
- 14) Air Force; 6 months active, 6 years reserve
- 15) N/A
- 16) Now
- 17) N/A

4. What civilian positions related to paint stripping have you held (if applicable) and number of years in those positions?

- 1) N/A
- 2) Chemical industries 15 years
- 3) Manufacturer of paint stripping equipment 22 years
- 4) Manager paint stripping project 2 years; Paint stripping R&D 1 year
- 5) Superintendent
- 6) Opened two plastic media stripping facilities in the past two years. International consultant on paint stripping
- 7) N/A
- 8) Air Force Program Management Office Staff Engineer responsible for AF technical data covering painting and stripping 3 years; Lead Engineer for AF Plastic Media Blasting Program 4 years
- 9) Facilities engineer for aircraft stripping/painting operations 2 years
- 10) Experimentation with PMB to find optimum parameters for stripping paint on thin skinned aircraft
- 11) Specifying equipment for PMB dry stripping
- 12) CO2 Laser technology 5 years
- 13) Manufacturer of plastic abrasives used to depaint 4 years

- 14) Manager of precision machine/functional dynamic aerospace component/energy related jobbing shop 17 years
- 15) Media manufacturing 7 years, equipment manufacturing 1 year
- 16) Program Manager 1 year
- 17) 15 years Advanced manufacturing engineer, 3 years Unit Chief Materials and Process, 1.5 years Senior Materials Engineer

5. What aircraft paint removal technology do you consider your specialty?

- 1) Chemical stripping
- 2) Plastic Media Blasting
- 3) Plastic Media Blasting
- 4) Not specific to one type, including helicopters (thin skinned), naval ship paint stripping, equipment cleaning and stripping
- 5) Plastic Media Blasting
- 6) Plastic Media stripping equipment and training
- 7) Plastic Media Blasting and lasers, both on composites
- 8) Chemical and Plastic Media Blasting
- 9) Plastic Media Blasting
- 10) Plastic Media Blasting
- 11) Plastic Media Blasting
- 12) Laser paint removal
- 13) Dry Stripping
- 14) Plastic Media Blast
- 15) Plastic Media Blast
- 16) Laser Stripping
- 17) Shot blast, sandblast, glass bead clean, slurry blast, plastic grit blast

6. What other paint removal technologies have you had working experience in?

- 1) None
- 2) Chemical stripping, hand tool remover
- 3) Chemical stripping
- 4) Naval ship stripping, equipment stripping
- 5) Chemical stripping
- 6) Chemicals, sandblasting, steel grit/shot, laser, aluminum oxide, water stripping, glass bead, walnut shells, corn cob, water and sodium blasting, abrasive oil slurry, flash lamp
- 7) None
- 8) Flash lamp, laser, CO2 pellet blasting, walnut shells, glass bead blasting, sandblasting,

- cryogenic stripping, sodium bicarbonate blasting, water blasting, ultrasonic scraper, sanding
- 9) Chemical stripping
- 10) CO2 dry ice pellets
- 11) Chemical stripping, methylene chloride and phenol
- 12) Beads, Chemicals
- 13) Chemical stripping
- 14) Chemical, abrasion, heat, abrasive blast, cryogenic, vibratory, slurry, high pressure fluid wash
- 15) Plastic Media Blast equipment
- 16) Lasers
- 17) Chemical paint stripping, abrasive-mechanical-sanding, thermal heat torch

7. How many years working experience do you have in the technologies noted in questions 5 and 6?

- 1) 30 years in area of corrosion control and prevention, including plating, metal coatings, conversion coatings, primers and paints
- 2) 10 years
- 3) PMB 5 years, Chemical stripping occasional personal use
- 4) 3 years
- 5) PMB 3 years, Chemical 6 years
- 6) PMB 6 years, chemical and others (see #6) 23 years (some only in the past 6 years)
- 7) PMB and Lasers 2.5 years
- 8) 6 years total (mainly Chemical and PMB)
- 9) 2 years PMB and Chemical
- 10) PMB 2 years, CO2 pellets 1.5 years
- 11) PMB 3 years, Chemical 3 years
- 12) 5 years lasers, CO2 and chemical
- 13) Plastic abrasives 4 years, Chemical 15 years
- 14) PMB 4 years; Chemical, abrasion, heat, abrasive blast, cryogenic, vibratory, slurry, high pressure fluid wash 17 years
- 15) Plastic media blast 4 years
- 16) Lasers 1 year
- 17) 19.5 years

8. What other paint removal technologies do you possess knowledge of?

- 1) Plastic bead blasting, sanding, high pressure water, CO2 pellet blasting, flash lamp, laser
- 2) Walnut shell blast, hydroblast
- 3) Laser, CO2 blast, abrasive blast of all kinds, flash lamp, hand sanding, power sanding, chipping gun, flame, needle gun

- 4) Buildings, concrete
- 5) None
- 6) Chemicals, sandblasting, steel grit/shot, laser, aluminum oxide, water stripping, glass bead, walnut shells, corn cob, water and sodium blasting, abrasive oil slurry, flash lamp
- 7) Waterjet, CO2 pellets, flash lamps, cryogenically assisted abrasives, ultrasonic, liquid nitrogen blast, abrasives, sodium bicarbonate blast, grit blast, chemicals
- 8) Flash lamp, laser, CO2 pellet blasting, walnut shells, glass bead blasting, sandblasting, cryogenic stripping, sodium bicarbonate blasting, water blasting, ultrasonic scraper, sanding
- 9) Laser, flash lamp, water jet, bicarbonate slurry, CO2 pellets, hand sanding
- 10) Chemical, laser
- 11) Carbon dioxide pellets, laser, flash lamp
- 12) None
- 13) Heat lamp, CO2 pellets, laser, handsanding
- 14) CO2, laser, flash, artificial age
- 15) Chemical paint stripping
- 16) PMB, water jet, sandblast, sanding, very limited chemical and biological
- 17) None

Appendix D: Measurement Questions

Question #1

The logical iterations of stripping methods will evolve from chemical stripping to plastic media blast to laser stripping.

Strongly Agree Neutral Strongly Disagree

Question #2

Chemical stripping will be used in the future for:

KEY: Small Application - parts less than 18 cubic inches.
Component - radomes, tailcones, wingtips, etc..
Sub-assembly - wing, rudder, horizontal stabilizer,
etc..

Not Used	Small Application	Component	Sub Assembly	Complete Aircraft Stripping
1	1	1	1	1

Question #3

Chemical stripping will cease to be used for exterior airframe surface paint removal in how many years?

Now 4 8 12 16 20 Never

Question #4

Chemical stripping will continue to be used because of its' non-damaging effects on certain substrates.

Strongly Agree Neutral Strongly Disagree

Question #5

Plastic media blasting will be the interim method of choice for exterior airframe surface paint removal, but only until another removal method is perfected.

Strongly Agree	Neutral	Strongly Disagree
:	:	:

Question #6

Plastic media blasting will cease to be used for exterior airframe surface paint removal in how many years?

Now	4	8	12	16	20	Never
:	:	:	:	:	:	:

Question #7

Plastic media blasting will not be the predominant method because of its' effects on certain substrates.

Strongly Agree	Neutral	Strongly Disagree
:	:	:

Question #8

Plastic media blasting will become the predominant paint removal method for exterior airframe surface stripping in how many years?

Now	4	8	12	16	20	Never
:	:	:	:	:	:	:

Question #9

Plastic media blasting will be used in the future for:

KEY: Small Application = parts less than 18 cubic inches.
Component = radomes, tailcones, wingtips, etc..
Sub-assembly = wing, rudder, horizontal stabilizer, etc..

Not Used	Small Application	Component	Sub Assembly	Complete Aircraft Stripping
:	:	:	:	:

Question #10

Laser stripping will become the predominant exterior airframe surface paint removal method in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : : :

Question #11

Laser stripping will not become the predominant exterior airframe surface paint removal method because of technical difficulties.

Strongly Agree Neutral Strongly Disagree
: : : : : :

Question #12

Laser stripping use will not become the predominant exterior airframe surface paint removal method because of its' high equipment costs.

Strongly Agree Neutral Strongly Disagree
: : : : : :

Question #13

Laser stripping will be used in the future for:

KEY: Small Applications - parts less than 18 cubic inches.
Component - radomes, tailcones, wingtips, etc..
Sub-assembly - wing, rudder, horizontal stabilizer,
etc..

Not Small Sub Complete
Used Application Component Assembly Aircraft
: : : : : : : : : : : :
: : : : : : : : : :

Question #14

Another method (excluding chemical, plastic media blasting, and laser stripping) will become the predominant exterior airframe surface paint removal method in the future.

Strongly Agree Neutral Strongly Disagree
: : : : : :

Question #15

Plastic media blasting is fully developed and requires no future research.

Strongly Agree Neutral Strongly Disagree
: : : : :

Question #16

The plastic media used for the plastic media blasting process will become optimized for exterior airframe surface paint removal needs in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : : :

Question #17

Plastic media blasting parameters will become optimized for exterior airframe surface paint removal needs in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : : :

Question #18

Plastic media blasting will become suitable for use on composites in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : : :

Question #19

Laser stripping parameters will become optimized for exterior airframe surface paint removal needs in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : : :

Question #20

Laser stripping will become suitable for use on composites in how many years?

Now 4 8 12 16 20 Never
: : : : : : :

Question #21

Robotic technology must develop concurrently with laser technology for laser stripping to work.

Strongly Agree Neutral Strongly Disagree
: : : :

Question #22

Robotic applications appropriate for a paint stripping environment will become developed and in use with either PMB, laser or another method for exterior airframe paint removal in how many years?

Now 4 8 12 16 20 Never
: : : : : : :

Question #23

Worker safety equipment that environmentally protects the worker while applying chemical stripping procedures will become available in how many years?

Now 4 8 12 16 20 Never
: : : : : : :

Question #24

Chemical stripping poses a serious threat to the worker's health. The only way to use chemical stripping safely is to remove the worker completely from the stripping environment.

Strongly Agree Neutral Strongly Disagree
: : : :

Question #25

Plastic media blasting worker safety equipment that environmentally protects the worker will become available in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : :

Question #26

Plastic media blasting must have specific facilities built that safely collects dust and paint chips.

Strongly Agree Neutral Strongly Disagree
: : : : : :

Question #27

Laser beams are harmful to anyone in the stripping area. The technology that reduces the beams' harmful effect to a safe level while successfully performing stripping operations will become available in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : :

Question #28

Laser stripping must have dedicated facilities precisely built for the laser to safely strip an exterior airframe surface.

Strongly Agree Neutral Strongly Disagree
: : : : : :

Question #29

Chemical stripping will become banned from use because of environmental regulations in how many years?

Now 4 8 12 16 20 Never
: : : : : : : : :

Question #30

Plastic media disposal regulations will restrict its use for exterior airframe surface paint removal in how many years?

Now 4 8 12 16 20 Never
: : : : : : :

Question #31

Laser stripping will evolve as the predominant exterior airframe surface paint removal method because of strict waste disposal regulations that ban or economically effect other methods.

Strongly Agree Neutral Strongly Disagree
: : :

Question #32

Application equipment technology and dedicated facility design, regardless of method, will become increasingly important in light of future handling, disposal, and air quality regulations.

Strongly Agree Neutral Strongly Disagree
: : :

Question #33

New paint removal methods (other than chemical, plastic media blast, and/or laser stripping) will evolve and become the predominant method because of handling, disposal, and air quality regulations.

Strongly Agree Neutral Strongly Disagree
: : :

Question #34

Robotics will not replace physical paint removal labor.

Strongly Agree Neutral Strongly Disagree
: : :

Question #35

In how many years will robotics become adaptable (programmable) to generate the precise movements needed to strip complex exterior airframe shapes.

Now 4 8 12 16 20 Never
: : : : : : : :

Question #36

A robot's mechanical reliability and ease of maintenance are primary concerns governing robotic adaptability in a aircraft paint removal environment.

Strongly Agree Neutral Strongly Disagree
: : : :

Question #37

Plastic media blasting equipment that restores air quality to an environmentally safe level will be developed in how many years?

Now 4 8 12 16 20 Never
: : : : : : : :

Question #38

Plastic media blasting dust is explosive. The technology that will reduce the explosiveness to a safe level will be available in how many years?

Now 4 8 12 16 20 Never
: : : : : : : :

Question #39

Plastic media recycling equipment that effectively separates heavy particles will become available in how many years?

Now 4 8 12 16 20 Never
: : : : : : : :

Appendix E: Second and Third Iteration Comments

Question #1

The logical iterations of stripping methods will evolve from chemical stripping to plastic media blast to laser stripping.

Second Iteration Comments.

- I feel PMB will largely replace chemical stripping, but I am still uncertain about laser stripping.

- It is too early to determine that laser stripping will "make it" (Laser stripping economy, safety and technical soundness are not yet proven).

- Laser stripping will probably never completely replace plastic media blasting.

- Laser is so far away from practical production use that without your definition of the time frame, no answer is possible.

- In the future, I do not think that any single method will have a monopoly in stripping aircraft, but the iteration you mentioned above represents the general trend.

- If laser technical problems can be solved.

- Recently, we have become very optimistic about the frozen CO2 bead blasting process.

- Need to understand effects of high energy substrates.

- This is dependent on the evolution of aerospace structural materials.

Third Iteration Comments.

- I agree with the first four comments made during the second iteration.

Question #2

Chemical stripping will be used in the future for:

Second Iteration Comments.

- Advanced thermal/chemical materials-combinations may be developed for rapid stripping; also, no known electro-chemical strippers known.

- Chemical stripping is not authorized on composite or advanced composite parts and will never be authorized due to incompatibility. Chemical strip may retain importance for small and/or delicate parts.

- Chemicals will continue to be used, I think, for:
 - small parts with complex geometric.
 - radomes and composite parts too thin or delicate to use PMB and which have resin systems which will not degrade due to the chemicals.
 - any application (usually of small areas) in which PMB or laser equipment is not available (i.e. field units).

- Use of chemicals will probably never completely cease unless PMB and laser equipment become less expensive and complicated to use.

- Only on those parts for which other stripping methods are not feasible.

Third Iteration Comments.

- After reconsideration, chemical stripping will probably see future use primarily on small applications. However, some components will still be done with chemical stripping.

- Chemical stripping will always be used, but not on a commercial basis.

Question #3

Chemical stripping will cease to be used for exterior airframe surface paint removal in how many years?

Second Iteration Comments.

- Depends upon your location and who is performing the stripping (i.e. private, industry, or government(DOD)).

- There will be individual pockets where chemical stripping will survive for very long times.

- Do not have data on holistic pattern or trend as coatings change, so should stripping materials.

- Significant reductions during next 2 to 6 years. Probably no chemical stripping of entire exterior surface of aircraft in Air Force within 6 years.

- Depending on definition of "cease" as the comments from the second iteration indicate.

- Depends upon your location and who is performing the stripping (i.e. private, industry, or government(DOD)).

- There will be individual pockets where chemical stripping will survive for very long times.

Third Iteration Comments.

- No comments given.

Question #4

Chemical stripping will continue to be used because of its' non-damaging effects on certain substrates.

Second Iteration Comments.

- Delicate metal parts or thin skin areas.

- I am not sure if local energizing of environmental compatible materials would work.

- Only when other techniques are unacceptable.

- Environmental problems.

- Until something better comes along (i.e. PMB, lasers, or ?), chemicals will probably be continued to be used even if only in very limited applications.

Third Iteration Comments.

- I do not foresee chemical stripping (or any other method) being completely done away with.

- Chemicals will continue to be used but the reason for continued use is not because of "non-damaging effects," but for reasons previously cited. The reason for the disparate answers may be due to confusion over the two-part nature of the question/proposal.

- Waste handling problems/cost will override any current economics.

- Chemical stripping will occur at "bandit" operations along the areas where labor is cheap and people can dump chemicals without detection. Chemicals damage substrates, the words "non-damaging" is a misleading statement and makes this a poor question. Yes, chemicals will continue to be used just like "crack" is still being used...even though both may soon be outlawed. Both do "structural damage"...but they still will be used.

Question #5

Plastic media blasting will be the interim method of choice for exterior airframe surface paint removal, but only until another removal method is perfected.

Second Iteration Comments.

- New method would have to be cheaper, less damaging (potential damage), and produce less hazardous waste.

- Dry coatings removal-elimination of blast/moisture intrusion should be a preferred choice.

- Robotics coupled with PMB will keep PMB effective for many, many years.

- But again, like chemicals, PMB will probably never be totally replaced.

Third Iteration Comments.

- I strongly disagree, since I feel that PMB is the best method available, now and in the foreseeable future. Beyond that, I guess that the question is rhetorical, since "all things must change."

- I think lasers, CO2 blasting, and sodium bicarbonate blasting have all demonstrated good potential and some method will eventually replace PMB.

Question #6

Plastic media blasting will cease to be used for exterior airframe surface paint removal in how many years?

Second Iteration Comments.

- Just the same as processes such as hand sanding, it will always be around.

- Depending upon the aircraft, PMB maybe used for a long time to come.

- Possibility of plating/de-plating of coatings superior to that of which we are familiar may occur. Painting is archaic, corrosion prevention is in its infancy.

- The next step in paint removal is now envisioned as laser stripping. Laser stripping will require expensive and technically complex systems that will have to be managed at depot facilities. PMB will probably remain the method of choice for contract or mid-level depaint facilities. However if a new method were developed that was technically simple, it would probably require 10 years to fully incorporate at all Air Force facilities.

Third Iteration Comments.

- Comment the term "plastic media" as we know it will probably change to a "composite media." Blast-dry stripping should continue for a long time.

- I'll stick to my original answer here under the following assumptions: PMB will never disappear totally; PMB will be replaced in 8-12 years as the method of choice for exterior airframe paint removal.

Question #7

Plastic media blasting will not be the predominant method because of its' effects on certain substrates.

Second Iteration Comments.

- Again new forms of media may be developed; "plastic" is a very general term.

- Waste disposal may be as much a deterrent as the damage.

- Special techniques will have to be developed for different substrates. The process will have to be specially controlled in some cases. Plastic media may not be used, but it will not be because of the substrate it will be caused by what is bonded to it. Another reason for not using plastic media is it maybe more economical for certain pieces to be done with another technique.

- Waste production will probably be the major issue.

- I agree with the statement that PMB "...will not be the predominant method" but not with the statement

"...because of its effects on certain substances." PMB's effect on certain substrates will prevent its use on those substrates but I believe that the major reason why it will not be the "predominant method" in the future is that it still produces a lot of waste, waste which is not produced by lasers.

- Its "so called" bad effects on certain substrates is due to the lack of proper testing (use cheaper machinery that can not control media flow, cleanliness, and particle size).

Third Iteration Comments.

- Experience with new media and optimization of operating parameters indicates that properly controlled PMB can be used on any surface.

- Its "so called" bad effects on certain substrates is due to the lack of proper testing (use cheaper machinery that can not control media flow, cleanliness, and particle size).

- Based on the following comments from the second iteration:

-- Waste disposal may be as much a deterrent as the damage.

-- Waste production will probably be the major issue.

-- I agree with the statement that PMB "...will not be the predominant method" but not with the statement "...because of its effects on certain substances." PMB's effect on certain substrates will prevent its use on those substrates but I believe that the major reason why it will not be the "predominant method" in the future is that it still produces a lot of waste, waste which is not produced by lasers.

I'll change my answer from strongly agree to disagree. Waste will probably be the dominant determining factor.

Question #8

Plastic media blasting will become the predominant paint removal method for exterior airframe surface stripping in how many years?

Second Iteration Comments.

- This is difficult for me to answer. At the present time, the majority of aircraft are still being stripped using chemicals (I believe). The momentum to switch to PMB is present, but will the depots convert from chemicals to PMB with the prospect of converting to lasers looming in the future? The trend may point to direct conversion from chemicals to lasers which would prevent PMB from ever being considered as predominant.

- During the next 4 years it will become the predominant paint removal method. Most of the smaller aircraft will use PMB in a production mode during FY89 (F-111 and smaller). Larger aircraft will phase into use during FY90-92 time frame.

- Exciting in term of new alloys of old materials.

Third Iteration Comments.

- Considering the marginal progress/conversion that has been made in the past year, I can't believe PMB will be predominant in two years.

- The EPA will soon force discontinuance of chemical stripping. PMB will be the only established technology available for some time to come.

Question #9

Plastic media blasting will be used in the future for:

Second Iteration Comments (Consensus Obtained).

- This is dependent on the types of materials.

- Rather than "small applications", more likely it will be specialized applications where other stripping methods are unacceptable.

- Some components will probably be done by other techniques because of costs or safety reasons.

- All painted surfaces except single fiber wound radomes.

- Similar comments apply as for this same question regarding chemicals.

Question #10

Laser stripping will become the predominant exterior airframe surface paint removal method in how many years?

Second Iteration Comments.

- If it ever does take over it will take 16 to 20 years to do so.

- It's possible sometime in the future, but there are many unknowns and unanswered questions that may prove laser stripping will never happen. On the other hand it may happen in the next 5-10 years.

- Possibly never, see earlier comment.

- First system could be developed in five years. It would probably take an additional five to ten years to incorporate at other Air Logistics Centers.

- Difficult to assess. I have no experience with coherent light energy source control; especially on complex shapes and materials.

Third Iteration Comment.

- In reference to: "Difficult to assess. I have no experience with coherent light energy source control; especially on complex shapes and materials," neither does anyone else, when the possible coating/substrate combinations are added into the problem.

Question #11

Laser stripping will not become the predominant exterior airframe surface paint removal method because of technical difficulties.

Second Iteration Comment.

- Unknown at this time.

Third Iteration Comments.

- "Technical difficulties" which look insurmountable now, may cease to pose problems in the future due to new solutions.

- I still feel that this is so, but not because of "technical difficulties," just difficulties of all types.

- Suspect the answers to this one are strongly biased by the individuals knowledge or lack of knowledge of laser processing.

Question #12

Laser stripping use will not become the predominant exterior airframe surface paint removal method because of its' high equipment costs.

Second Iteration Comments.

- Good robotic PMB equipment for large aircraft (747, 707, C5A, etc.) will be just as expensive. About \$20 million plus the facility for a PMB set-up. I feel PMB will be so well established that to convert to a process just as expensive (equipment wise), and at no cost savings or increase in speed will be foolish.

- Very possible that laser stripping will work fine but be economically feasible. Still, again it's not known at this time; no one has an industrial laser paint stripper.

Third Iteration Comments.

- Agree with comment that a laser stripping facility will cost the same as a PMB facility. Now the question is . operating costs. Too many unknowns for me to predict who's high and who's low.

- But this is only one reason, not the reason.

- High equipment costs will depend upon the depth to which laser paint removal will penetrate the paint stripping market.

Question #13

Laser stripping will be used in the future for:

Second Iteration Comments.

- Possibly all the above.

- Where the combination is as follows:

- Resilient coating on thin-skin composite substrate.
- Thin kevlar with epoxy primer.
- Any foam substrate.

Third Iteration Comment.

- Boron, graphite epoxy, carbon epoxy, carbon aramid, aramid, glass composites, kevlar, permali, honeycomb sandwich, ferobestos, divinycell, TBD core, plastic to metal bonds, composites to metals bonds, thermo-plastic structural matrix, aluminum lithium alloy, and K'Karb are only a few of the composites. Over 100 more are expected in the next 10 years. Each has a different reflection rate and absorption coefficient. This will drive a laser crazy trying to adjust as it passes from one surface to another. It's possible, but expensive. It would be much easier to adjust the pressure, flowrate, and angle of a robotic PMB machine to remove paint without substrate damage. Normally, sub-assemblies are of the same materials and would be easier to do. It would be cheaper for a computer controlled indexing cabinet to PMB strip small complex shaped items.

Question #14

Another method (excluding chemical, plastic media blasting, and laser stripping) will become the predominant exterior airframe surface paint removal method in the future.

Second Iteration Comments.

- Again, coatings are in their infancy. Human skin can be shed/peels under certain applied energy sources; coatings can be taught to perform under certain stimulus.

- New methods are likely to be invented. One possibility is water jets; advantages: minimization of waste, contamination of waste, operator protection, facility flexibility, economy.

- I believe new techniques will develop in the near future that will be better than any of the present ideas.

- Who knows?

- Biological stripping is a possibility.

- CO2 bead blasting 1-2 years.

- Special paints designed for ease of removal by electro-chemical methods; 10 years.

- Beware of any answers that say water and bi-carb soda will be a future contender for an effective stripping method. These people do not understand the corrosive effects of baking soda + water + aluminum and the problems of primer

and paint disbond with soda residue. It is almost impossible to filter out the small paint chips and soda from the waste water slurry.

Third Iteration Comments.

- Dupont along with other corporations are building a \$500 million plastic recycling plant and will take all types of junk plastic and recover the resins. They will also take back the used plastic medias. PMB may become cheaper, even if oil prices go up. As aircraft composites are used more frequently, PMB will be the choice, if aviation quality equipment reaches the users. So far, no one has had enough smarts to order good equipment.

- What time frame?

- CO2 bead blasting 1-2 years.

Question #15

Plastic media blasting is fully developed and requires no future research.

Second Iteration Comments.

- I feel PMB has been studied very completely. However, there are areas that could be developed further (i.e. hazardous waste reduction, media improvement).

- Composites research complete in late 88, approval for composite granted in Jan 89.

- The world changes continually; as coatings change, so will removal techniques.

- Need: optimization with respect to potential damage; recycle optimization; waste separation and handling; waste treatment and disposal; media optimization; more information and confidence; adjustment to new (future) materials; automation.

- Further research is required for separation (cleaning) techniques for recycled PMB as well as for robotic control, effects of PMB on new (perhaps as yet undiscovered) surfaces, and in developing new PMB media.

- OK for "job shop" operations, but must be integrated with robotics, feedback control, etc. for large scale stripping. Also, further development/refinement required to quantify and minimize composite damage.

- Composites are not hard problems to resolve! Thin aluminum are the problem.

Third Iteration Comment.

- Since the statement is not true, I will move my answer to the modal.

Question #16

The plastic media used for the plastic media blasting process will become optimized for exterior airframe surface paint removal needs in how many years?

Second Iteration Comments.

- There will always be room for further improvement.
- 2 years.
- Should not take long if funding is provided in significant amounts.

Third Iteration Comments.

- Agree with never, but it will be close in 2 years.
- An energetic, competent "overseer" with the \$ and power to properly investigate, experiment and evaluate equipment, technique, material and the effect on materials is needed. The industry is rife with poorly conceived tests/plans, unsupported claims, and "snake-oil salesmen" who are more interested in short term profit than properly implementing this technology.

Question #17

Plastic media blasting parameters will become optimized for exterior airframe surface paint removal needs in how many years?

Second Iteration Comments.

- Depends on recognizing the problem and funding. 2 years to recognize and define the problem and fund; 4 years research, develop, and evaluate; 2 years paperwork and preparations; "X" years to implement.
- This relates to European testing and optimization. The U.S. manufacturers are 8-12 years behind the Europeans. The U.S. Navy will have their substrates optimized by

August-September 1989. The USAF will lag years behind the Navy in parameter development.

- Each new substrate material or thickness may require different parameters. Therefore, this is really an on-going area of study and concern.

Third Iteration Comments.

- Theoretically, the answer to this could be "never" since parameters will always need to be developed for new bead material. However, present parameters are very close for use with existing media.

- Too many combinations exist to have a panacea approach make optimization any sooner.

- Could be done in 2 years if adequately funded.

Question #18

Plastic media blasting will become suitable for use on composites in how many years?

Second Iteration Comments.

- With the correct machinery, any composite can be stripped (except single strand, filament wound objects). I should have a \$2.5 million robotic computer controlled composite helicopter blade PMB stripping machine in operation by December 1989. At present, only very delicate hand sanding is allowed on these blades and damage occurs.

- In controlled conditions with skilled and informed operators (now).

- Air Force has authorization.

- Reports from AFWAL (now called WRDC - Wright Research and Development Center), the Naval Air Development Center, and Ogden Air Logistics Center at Hill AFB show that, if done correctly (i.e. using PMB to remove only the paint and leave the primer), PMB is safe for use on composites.

- Some have been tested and parameters determined as of this date.

Third Iteration Comments.

- Depends on your definition of "suitable".

- Too many combinations exist to have a panacea approach make optimization any sooner. Refer to 1Lt Larry Butkus' report and Joe Kozol's NADC 88109-60 "The Effects of PMB Paint Removal on the Microstructures of Graphite/Epoxy Composite Materials". Other composite combinations need some accurate evaluations also.

Question #19

Laser stripping parameters will become optimized for exterior airframe surface paint removal needs in how many years?

Second Iteration Comments.

- Funding not withstanding.
- 5 to 10 years depending on technological developments.
- Partial areas only!

Third Iteration Comments.

- No comments given.

Question #20

Laser stripping will become suitable for use on composites in how many years?

Second Iteration Comments.

- Partial areas only!
- 5 to 10 years.
- Composites are changing so rapidly, that laser may take years to develop correct parameters based on absorption ratios.

Third Iteration Comments.

- If the mode for laser optimization is 8 years in the previous question, how come this one is 12? Does optimization not include composites.
- As suitable as it will get.
- Lasers will not be used depending on absorption ratios of the composites. Lasers depend on absorption ratios

by the paint. It has been demonstrated that lasers can safely be used on composites (WRDC/MLSE contract & NAVAIR efforts).

Question #21

Robotic technology must develop concurrently with laser technology for laser stripping to work.

Second Iteration Comments (Consensus Obtained).

- Needs to be a fully automated technology.
- The new robotic (electric) technology with 720 degrees rotation, seven axis, six DOF, teach-in, and visual input is now available. Laser robots only need an enhanced visual system with multiple parallax system inputs so curves and paint surface depths can be determined.

Question #22

Robotic applications appropriate for a paint stripping environment will become developed and in use with either PMB, laser or another method for exterior airframe paint removal in how many years?

Second Iteration Comments.

- The Danes (Danish Gout) has already ordered two PMB stripping robots, and each one can outstrip 10 men. With normal paint thickness, a (1) robot can out perform 20 men.
- Robots will be installed in a PMB booth at Ogden ALC in, hopefully, this calendar year. How long it will take to optimize their use is anybody's guess.
- Depends primarily on funding!
- Due to potential for radical differences in coating thickness encountered while stripping an aircraft with service time (application variations, spot painting, erosion, partial re-paint, panel replacement, etc.), "real time" observation of the stripping process is necessary in order to control traverse rate, dwell time, etc. If a programmed "nominal" rate is established and used either over or under exposure is possible. "Under" is just going to leave some paint on, but "over" has damage potential.
- First robotic PMB paint stripper due to be operational late 89 at Hill AFB. Second unit will be at Robins AFB in 1990.

Third Iteration Comments.

- Robotics themselves are not the pacing item. The sensor(s), which allow "human-like" observation of the work in progress and enable the alteration of nominal-programmed parameters to suit the situation, are!

- Adequate feed-back control is going to take several more years.

Question #23

Worker safety equipment that environmentally protects the worker while applying chemical stripping procedures will become available in how many years?

Second Iteration Comments.

- Isolate worker from hazardous environment.

- No matter how much safety gear we equip a chemical stripping employee with, he/she still gets burns from chemicals and are still exposed to chemical vapors!

- I don't know enough to correctly answer this, but the equipment which is currently marketed and/or in use must not be effective or is not used correctly judging by the continuing bad reports from the field.

- But very cumbersome, uncomfortable, and inefficient (now).

- One could argue that equipment exists today. However, for various reasons it does not function as intended (poor up-keep/maintenance, worker indifference, etc.).

Third Iteration Comment.

- It will never be perfect.

Question #24

Chemical stripping poses a serious threat to the worker's health. The only way to use chemical stripping safely is to remove the worker completely from the stripping environment.

Second Iteration Comments.

- However, even if the employee is out of the work environment we still are omitting VOCs into the air and

toxic organic into the waste water which needs treatment before it leaves the facility or base.

- Protective clothing and procedures are/can be developed to allow human interaction.

Third Iteration Comment.

- Hey! How can this mode be strongly agree when the mode for the previous answer was that the necessary protective gear already exists?

Question #25

Plastic media blasting worker safety equipment that environmentally protects the worker will become available in how many years?

Second Iteration Comments (Consensus Obtained).

- The use of cotton blast suits, cotton gloves, ear plugs, a sound deadening hard helmet with hospital grade clean air, and leather shoes is all that is required. The worst hazard is tripping over one's own air hose. With a battery pack breathing package, even this is eliminated.

- Heavy, cumbersome, and inefficient.

- Equipment exist; however, it will probably be improved over the next 4 years.

- We are not dealing with a vapor, we are dealing with a dust and we can now control the worker's exposure by safety equipment including a supplied breathing air helmet.

- Standard safety equipment.

Question #26

Plastic media blasting must have specific facilities built that safely collects dust and paint chips.

Second Iteration Comments.

- Facilities capable of walnut shell blasting should be compatible with PMB.

- There is a possibility of local containment which requires development and must be economical. Maybe required for a very large aircraft.

- Almost any facility can be converted with reverse pulse air filters.

- (question changed to ...must have a specific method that safely...) "There's more than 1 way to skin a cat!"

- Special systems can be designed to get around this problem.

Third Iteration Comment.

- How is "facility" defined. If it means a separate building with separation equipment, I'll disagree. If it is simply a piece of equipment or method, I'll agree.

Question #27

Laser beams are harmful to anyone in the stripping area. The technology that reduces the beams' harmful effect to a safe level while successfully performing stripping operations will become available in how many years?

Second Iteration Comments.

- I think the statement in this question is not correct. However, the "beam delivery" problem is an area that needs engineering along with the whole laser technology.

- Depends on \$\$ allocated.

- Not a good question. The safety shut-off technology is now available to shut off the input flash lamp if an unsafe condition exists. Since the focal plane of light emissions must be so fine to concentrate heat and allow depth perception adjustments, the actual laser "ray" itself will always be a potential hazard. Such things as scatter shield reflective clothing and chemical light residue eye shield are now available.

Third Iteration Comment.

- The key to this question is "while successfully performing the stripping operation." The mode for question #19 is 8 years; therefore, how can this answer be less than 8 years.

Question #28

Laser stripping must have dedicated facilities precisely built for the laser to safely strip an exterior airframe surface.

Second Iteration Comments.

- Beam containment and safety systems must be integrated into the design, but use of a hand held field unit is feasible.

- I feel it would be possible to convert an existing facility to a laser stripping cell. At least I feel a fighter size PMB booth could be modified to house laser stripping.

- You can modify a facility. The end effector robotic head would contain the visual system, fume removal suction, laser curtain, and laser gun. It is possible to use any hanger with locks on all doors and shielded wiring.

Third Iteration Comment.

- An unshielded flash lamp is the dangerous item. The laser beam is not so dangerous, for it requires a focal ranging and very precise stand off distance. We can either make an exotic hanger/facility or put our money in a good machine with proper ventilation systems. Robotic applications are the only cost effective methods for large areas. Robots can be coated with scatter beam material for added safety.

Question #29

Chemical stripping will become banned from use because of environmental regulations in how many years?

Second Iteration Comments.

- Certain chemicals are environmentally safe, but most are not and will be stopped if they have not already done so.

- "use" referring to widespread or uncontrolled use.

- Function of locality and time.

- By 1992 we will see significant reductions in the use of chemical strippers due to environmental legislation.

- Technology now exists to recycle and reconstitute stripping compounds.

- In certain states because of disposal problems.

- In some regions I am told (now).

- Chemicals are a broad field as are plastics. The year 2000 should prove a new era in technology.

- Depending upon your location.

Third Iteration Comments.

- In most cases.

- Chemical stripping (as we now know it: phenol-based and methylene-chloride based strippers) is now banned in many areas, I am told. New chemicals may be developed, but I believe there is enough of a stigma against chemicals that these new products will not be developed/used before existing ones are banned.

Question #30

Plastic media disposal regulations will restrict its use for exterior airframe surface paint removal in how many years?

Second Iteration Comments.

- Unknown. If this happens we cannot strip period! The only reason PMB waste is hazardous is the chromium and cadmium. Primarily the problem is chromium and that comes from the primer that is being removed.

- The stripping of aircraft on earth may differ from that in orbit or on a space platform. I assume that all operation are done on earth.

- Plastic media is a disposal concern because of the lead and chromates in the paint and the cadmium plate on the aircraft surface. Any paint removal method will continue to produce these waste as long as the paints contain these compounds. Chemical strippers are an environmental hazard in their own right while laser and plastic rather benign.

- Costs may be high.

- Plastic media itself is not known to be a problem, just the hazardous components introduced into it during the stripping of coatings which may contain (among other things) lead, chromates, cadmium, and zinc. If necessary, present technology can remove most or all of these objectionable components.

- This is dependent on coating development that will protect against corrosion without the presence of heavy metal such as chromates.

- Acrylics and styrene based plastics can pose a disposal problem.

- The regulations may never prohibit its use, but the disposal expense will make it uneconomical.

- With the research into used plastic media, we can use it to turn liquid chemical waste into gels. By burning the media, we can heat our hangers, electrically remove all hydrocarbons to sell to paint companies and scrub other volatiles. We can reduce our waste volume by 90%.

Third Iteration Comments.

- The key word here is "restrict." If this were changed to "prohibit" I'd answer never.

- The regulations will make it uneconomical.

Question #31

Laser stripping will evolve as the predominant exterior airframe surface paint removal method because of strict waste disposal regulations that ban or economically effect other methods.

Second Iteration Comments.

- Degraded paint chips will still be a disposal problem.

- If lasers become the predominant method then yes I think the driver will be environmental issues.

- The vaporation of the objectionable materials only compounds the problem.

- Laser vapors maybe considered just as harmful as those in the PMB blast furnace...thus it's which is the worst of two evils.

Third Iteration Comment.

- If lasers become the predominant method then yes I think the driver will be environmental issues.

Question #32

Application equipment technology and dedicated facility design, regardless of method, will become increasingly important in light of future handling, disposal, and air quality regulations.

Second Iteration Comment.

- No comments given.

Third Iteration Comment.

- No comments given.

Question #33

New paint removal methods (other than chemical, plastic media blast, and/or laser stripping) will evolve and become the predominant method because of handling, disposal, and air quality regulations.

Second Iteration Comments.

- A benign method (possibly biological) will evolve in 10 to 20 years.

- Changes may be gradual 15 to 30 years by: command destruct paints; paint substitutes; self protecting surfaces; lifetime paint; nontoxic paint.

- Most of my past comments touch on the question of coating developments. New coating, new compositions to prevent the degrading effects of the environment should improve. Skins that can be taught to react to various stimuli may help reduce degradation or may be self renewing.

- Biological methods are being researched by Warner Robbins AFB. These have shown some promise, especially since they do not result in any toxic wastes to be disposed of.

- CO2 bead blasting in 1-2 years. I can not discuss the details.

- Special paints designed for ease of removal by electro-chemical methods in 10 years.

- I feel once research is done in "isolation of resonate frequencies," we will be able to harden paint with a highly absorptive chemical with low/no VOC. By hooking the painted surface to an input device, we can vibrate only the paint at the designated destructive resonate frequency and

shatter the paint into millions of tiny particles. The water based lacquers may be the answer.

Third Iteration Comments.

- CO2 bead blasting or similar technology. New paints will be developed that are easily removed with special methods.

- Most of my past comments touch on the question of coating developments. New coating, new compositions to prevent the degrading effects of the environment should improve. Skins that can be taught to react to various stimuli may help reduce degradation or may be self renewing.

Question #34

Robotics will not replace physical paint removal labor.

Second Iteration Comments.

- There will still be areas and times manual paint removal will be necessary.

- With robotics, the operators will be located in a computer control room. There maybe a marginal reduction in the labor force required.

- There will be always some labor component or special needs.

- Capital vs. labor intensiveness is a trade off decision that we will always face.

- Human labor will become too expensive. Aircraft downtime is expensive. When a 747 takes 10 days to strip and 4 robots can do the same job in 5.8 hours... then you can see why robots will be used.

Third Iteration Comments.

- Robots will never be able to completely replace physical labor as long as parts and paints are not designated with robotic paint stripping as a design factor.

- Robotics is too loose a term. If it includes a human observer with decision making overriding input, then I feel that such a system is a probable next-step situation.

- For large aircraft, it is a must. Take the C-5A for an example, it's strictly economics! Twenty people manning stripping hoses; 5000 cfm air compressor; \$1.6 million

handling equipment; floor sweepers; safety inspectors; 24,600 pounds of plastic media consumed; 3,500 pounds of paint chips to remove; 28,100 pounds of waste to dispose, etc... A good robotic machine coupled with an "aviation quality PMB machine" will: outstrip 20 men per end effector; only consume 7,390 pounds of plastic media; separate the paint from the dust, allowing only disposal of the paint; eliminate expensive hanger ventilation; no sick days; no coffee breaks.

- Will not replace it completely.

Question #35

In how many years will robotics become adaptable (programmable) to generate the precise movements needed to strip complex exterior airframe shapes.

Second Iteration Comments.

- Schlick Corporation of Germany has already reached this programmable technology.

- If you have the \$\$\$!!!

- It's not just movement that's the problem, it's the lack of sensors capable of duplicating an operator's eyesight, and decision-making controllers which can interpret what is seen in order to modify technique in real-time!

- 1 to 5 years if funding is adequate.

Third Iteration Comments.

- Movements are O.K. now; access is a problem & so is the input (visual, etc...) necessary to control the process properly!

- The technology is already here. The French already use visual feedback with binary color coded recognition to strip composites. Coating thickness may vary, but the robot can stop at the primer or the substrate with 90% less damage than hand sanding. NASA has developed multi-parallax systems at the end effector to allow complex curves to be visualized. Three-D photography of an item, input into a computer with depth of field measurements can allow exact stripping information fed to the computer & end effector. Paint thickness measurements constantly feed the computer to vary media flow and velocity. It "ain't" as tough as it sounds!

Question #36

A robot's mechanical reliability and ease of maintenance are primary concerns governing robotic ada, ability in a aircraft paint removal environment.

Second Iteration Comments.

- There are many primary concerns. These are two of them.
- You must have low, low down time of the robot.

Third Iteration Comment.

- The electric robot is faster, more accurate, and reliable, but is not good in applications where the end effector is heavy. The hydraulic robot is great at carrying heavy end effector leads, but does not duplicate movements exactly and has a history of maintenance problems. A robot for large aircraft would have to be hydraulic, electric robots would be good for components. It takes about 2.5-3 years of programming for an effective robot.

Question #37

Plastic media blasting equipment that restores air quality to an environmentally safe level will be developed in how many years?

Second Iteration Comments.

- Technology exists today.
- The problem is more the paint not the media. When the paint becomes less toxic there will be pressure to match the media.
- The systems now available yet the air cleaner than it was when it entered the strip hanger. Good reverse pulse systems can clean the air to 99.98% down to 1 micron. This is cleaner than most "ultra clean rooms" in missile guidance system assembly plants. The British have developed a polyester filter material that stays like new for years.

- Air quality is not a problem.

Third Iteration Comment.

- No comments given.

Question #38

Plastic media blasting dust is explosive. The technology that will reduce the explosiveness to a safe level will be available in how many years?

Second Iteration Comments.

- Please refer to "Explosibility and Ignitability of Plastic Abrasive Media" NCEL Contract Report (CR87.011).

- Plastic media dust is not explosive under proper operating conditions. You use adequate ventilation in the hanger. The only area you get to explosive levels are in the bag house and they are already designed for this.

- Only acrylic and polyester pose a problem here!! Only potential for urea/melamins is in the dust collector system.

- I don't know enough to answer this.

- With required ventilation the levels of dust will not reach an explosive limit.

- The technology is probably available - the implementation will take time and need.

- The concentrations required to reach explosivity in a booth have never been achieved in a n Air Force blast booth. We would have had to of seen a 40 times increase in dust in our worst system to approach explosivity.

- This is a misnomer. Pulverized cow dung is also explosive, dried pulverized carrots, etc.. The studies done by the Navy, Dupont, and Union Carbide show an explosion can occur if a strong ignition source is present...but with any air movement, the flame propagation can not progress. With approximately 30 LIFM air flow and a good PMB machine that removes 99.5% of all dust.. you could not get an explosion if you tried. The air velocity is too great for flame propagation and the air cyclones would/could never allow an explosion. There are explosion in fuel tanks of F-15 aircraft all the time. No one worries.

Question #39

Plastic media recycling equipment that effectively separates heavy particles will become available in how many years?

Second Iteration Comments.

- Industry has produced several prototypes. We are awaiting data at this time.
- The technology is available. The pressure and \$\$ are needed.

Third Iteration Comments.

- Some promising techniques/equipment was recently shown at the "DOD/Industry Coatings Removal Conference," 11-13 April 1989, Fort Walton Beach, Fl.

Appendix F: Wilcoxon Signed Rank Test Results

Question #1

WILCOXON'S SIGNED RANK TEST FOR X1 - Y1

SUM OF NEGATIVE RANKS	-19.00
SUM OF POSITIVE RANKS	2.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.0469
<u>TWO TAILED P-VALUE</u>	<u>0.0938</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 3
NUMBER OF ZERO DIFFERENCES DROPPED 10
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 6 MISSING CASES 11

Question #2

WILCOXON'S SIGNED RANK TEST FOR X2 - Y2

SUM OF NEGATIVE RANKS	-3.500
SUM OF POSITIVE RANKS	2.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.3750
<u>TWO TAILED P-VALUE</u>	<u>0.7500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 13
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #3

WILCOXON'S SIGNED RANK TEST FOR X3 - Y3

SUM OF NEGATIVE RANKS	-9.500
SUM OF POSITIVE RANKS	18.50
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.2344
<u>TWO TAILED P-VALUE</u>	<u>0.4688</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 5
NUMBER OF ZERO DIFFERENCES DROPPED 8
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 7 MISSING CASES 9

Question #4

Only 2 experts changed their response; Statistix unable to calculate test.

Question #5

WILCOXON'S SIGNED RANK TEST FOR X5 - Y5

SUM OF NEGATIVE RANKS	-3.500
SUM OF POSITIVE RANKS	2.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.3750
<u>TWO TAILED P-VALUE</u>	<u>0.7500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 13
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #6

WILCOXON'S SIGNED RANK TEST FOR X6 - Y6

SUM OF NEGATIVE RANKS	-33.50
SUM OF POSITIVE RANKS	2.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.0117
<u>TWO TAILED P-VALUE</u>	<u>0.0234</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 4
NUMBER OF ZERO DIFFERENCES DROPPED 8
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 8 MISSING CASES 9

Question #7

WILCOXON'S SIGNED RANK TEST FOR X7 - Y7

SUM OF NEGATIVE RANKS	-11.00
SUM OF POSITIVE RANKS	4.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.2187
<u>TWO TAILED P-VALUE</u>	<u>0.4374</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 3
NUMBER OF ZERO DIFFERENCES DROPPED 11
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 5 MISSING CASES 12

Question #8

Only 2 experts changed their response; Statistix unable to calculate test.

Question #9

CONSENSUS OBTAINED ROUND 2.

Question #10

WILCOXON'S SIGNED RANK TEST FOR X10 - Y10

SUM OF NEGATIVE RANKS	-21.00
SUM OF POSITIVE RANKS	0.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.0156
<u>TWO TAILED P-VALUE</u>	<u>0.0312</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 3
NUMBER OF ZERO DIFFERENCES DROPPED 10
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 6 MISSING CASES 11

Question #11

Only 2 experts changed their response; Statistix unable to calculate test.

Question #12

WILCOXON'S SIGNED RANK TEST FOR X12 - Y12

SUM OF NEGATIVE RANKS	-3.500
SUM OF POSITIVE RANKS	6.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.3125
<u>TWO TAILED P-VALUE</u>	<u>0.6250</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 4
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 4 MISSING CASES 13

Question #13

Only 1 expert changed their response; Statistix unable to calculate test.

Question #14

WILCOXON'S SIGNED RANK TEST FOR X14 - Y14

SUM OF NEGATIVE RANKS	-3.000
SUM OF POSITIVE RANKS	3.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.6250
<u>TWO TAILED P-VALUE</u>	<u>0.9999</u>
TOTAL NUMBER OF VALUES WHICH WERE TIED	2
NUMBER OF ZERO DIFFERENCES DROPPED	13
MAX. DIFF. ALLOWED BETWEEN TIES	1.00E-05
CASES INCLUDED 3	MISSING CASES 14

Question #15

WILCOXON'S SIGNED RANK TEST FOR X15 - Y15

SUM OF NEGATIVE RANKS	-7.500
SUM OF POSITIVE RANKS	2.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.1875
<u>TWO TAILED P-VALUE</u>	<u>0.3750</u>
TOTAL NUMBER OF VALUES WHICH WERE TIED	2
NUMBER OF ZERO DIFFERENCES DROPPED	12
MAX. DIFF. ALLOWED BETWEEN TIES	1.00E-05
CASES INCLUDED 4	MISSING CASES 13

Question #16

Only 2 experts changed their response; Statistix unable to calculate test.

Question #17

WILCOXON'S SIGNED RANK TEST FOR X17 - Y17

SUM OF NEGATIVE RANKS	-4.500
SUM OF POSITIVE RANKS	1.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.2500
<u>TWO TAILED P-VALUE</u>	<u>0.5000</u>
TOTAL NUMBER OF VALUES WHICH WERE TIED	2
NUMBER OF ZERO DIFFERENCES DROPPED	13
MAX. DIFF. ALLOWED BETWEEN TIES	1.00E-05
CASES INCLUDED 3	MISSING CASES 14

Question #18

Only 2 experts changed their response; Statistix unable to calculate test.

Question #19

Only 2 experts changed their response; Statistix unable to calculate test.

Question #20

Only 2 experts changed their response; Statistix unable to calculate test.

Question #21

CONSENSUS OBTAINED ROUND 2.

Question #22

WILCOXON'S SIGNED RANK TEST FOR X22 - Y22

SUM OF NEGATIVE RANKS	-4.000
SUM OF POSITIVE RANKS	6.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.4375
<u>TWO TAILED P-VALUE</u>	<u>0.8750</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 4 MISSING CASES 13

Question #23

WILCOXON'S SIGNED RANK TEST FOR X23 - Y23

SUM OF NEGATIVE RANKS	0.000
SUM OF POSITIVE RANKS	6.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.1250
<u>TWO TAILED P-VALUE</u>	<u>0.2500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #24

Only 2 experts changed their response; Statistix unable to calculate test.

Question #25

CONSENSUS OBTAINED ROUND 2.

Question #26

Only 1 expert changed their response; Statistix unable to calculate test.

Question #27

WILCOXON'S SIGNED RANK TEST FOR X27 - Y27

SUM OF NEGATIVE RANKS	-7.000
SUM OF POSITIVE RANKS	3.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.3125
<u>TWO TAILED P-VALUE</u>	<u>0.6250</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 0
NUMBER OF ZERO DIFFERENCES DROPPED 11
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 4 MISSING CASES 13

Question #28

Only 1 expert changed their response; Statistix unable to calculate test.

Question #29

WILCOXON'S SIGNED RANK TEST FOR X29 - Y29

SUM OF NEGATIVE RANKS	-3.500
SUM OF POSITIVE RANKS	6.500
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.3125
<u>TWO TAILED P-VALUE</u>	<u>0.6250</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 4 MISSING CASES 13

Question #30

Only 1 expert changed their response; Statistix unable to calculate test.

Question #31

WILCOXON'S SIGNED RANK TEST FOR X31 - Y31

SUM OF NEGATIVE RANKS	-6.000
SUM OF POSITIVE RANKS	0.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.1250
<u>TWO TAILED P-VALUE</u>	<u>0.2500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #32

Only 2 experts changed their response; Statistix unable to calculate test.

Question #33

Only 2 experts changed their response; Statistix unable to calculate test.

Question #34

Only 2 experts changed their response; Statistix unable to calculate test.

Question #35

WILCOXON'S SIGNED RANK TEST FOR X35 - Y35

SUM OF NEGATIVE RANKS	-6.000
SUM OF POSITIVE RANKS	0.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.1250
<u>TWO TAILED P-VALUE</u>	<u>0.2500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 2
NUMBER OF ZERO DIFFERENCES DROPPED 12
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #36

WILCOXON'S SIGNED RANK TEST FOR X36 - Y36

SUM OF NEGATIVE RANKS	-16.50
SUM OF POSITIVE RANKS	28.50
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.2520
<u>TWO TAILED P-VALUE</u>	<u>0.5040</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 9
NUMBER OF ZERO DIFFERENCES DROPPED 7
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 9 MISSING CASES 8

Question #37

WILCOXON'S SIGNED RANK TEST FOR X37 - Y37

SUM OF NEGATIVE RANKS	0.000
SUM OF POSITIVE RANKS	6.000
EXACT PROBABILITY OF A RESULT AS OR MORE EXTREME THAN THE OBSERVED RANKS (1 TAILED P VALUE)	0.1250
<u>TWO TAILED P-VALUE</u>	<u>0.2500</u>

TOTAL NUMBER OF VALUES WHICH WERE TIED 0
NUMBER OF ZERO DIFFERENCES DROPPED 11
MAX. DIFF. ALLOWED BETWEEN TIES 1.00E-05
CASES INCLUDED 3 MISSING CASES 14

Question #38

CONSENSUS OBTAINED ROUND 2.

Question #39

Only 2 experts changed their response; Statistix unable to calculate test.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GLM/LSM/89S-67		5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION School of Systems and Logistics	6b. OFFICE SYMBOL (If applicable) AFIT/LSM	7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433-6583		7b. ADDRESS (City, State, and ZIP Code)	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.	PROJECT NO.
		TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) THE FUTURE OF AIRCRAFT PAINT REMOVAL METHODS			
12. PERSONAL AUTHOR(S) Michael J. Then, B.S., Capt, USAF			
13a. TYPE OF REPORT MS Thesis	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) 1989 September	15. PAGE COUNT 169
16. SUPPLEMENTARY NOTATION			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
11	11		
		Paint Removal, Forecast, Delphi Paint Stripping, Paint Theses, (5100)	
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
<p>Thesis Advisor: Donald C. McNeeley Instructor Department of Logistics Management</p> <p>Approved for public release: IAW AFR 190-1. <i>Larry W. Emmelhainz</i> LARRY W. EMMELHAINZ, Lt Col, USAF 11 Oct 89 Director of Research and Consultation Air Force Institute of Technology (AU) Wright-Patterson AFB OH 45433-6583</p>			
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Donald C. McNeeley, Instructor		22b. TELEPHONE (Include Area Code) (513) 255-4149	22c. OFFICE SYMBOL LSM

UNCLASSIFIED

→ The purpose of study was to develop a qualitative forecast for predicting aircraft paint removal methods. A Delphi methodology was used to create a technical forecast, combining the expectations of individuals who work with the related technologies on a daily basis.

The Delphi results yielded five major conclusions. First, the projected paint removal method that will suit future paint removal needs is PMB, and no other method is projected to be a serious threat to PMB's dominance. Second, PMB's process and parameters must be further researched to optimize the method's effectiveness. Third, the worker's safety can be further enhanced by both protective equipment that is available today, and facility construction that is specifically designed for the given removal method. Fourth, facility design is the major consideration when defining a paint removal's environmental effects. Lastly, it is undeterminable if robotics will replace human labor. Equipment that safely applies PMB is available today, while the equipment that further the method's effectiveness of separating heavy particles will be accessible in 1 year. Keywords:

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FLD 18

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